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*Editor*

ROY WALDO MINER

# DYNAMIC ANTHROPOMETRY

BY

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*Consulting Editor*

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*Conference Chairman and Consulting Editor*

EARL W. COUNT

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* This series of papers is the result of a Conference on Dynamic Anthropometry held by the Section of Biology of The New York Academy of Sciences. April 15 and 16, 1955.

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# STATEMENT OF GENERAL OBJECTIVES

*By* Earl W. Count
*Hamilton College, Clinton, N. Y.*

When, in 1947, the United Nations' Commission on Human Rights opened the discussion on its agenda, the delegate from Lebanon proposed that it should begin with the question, What is Man?

I understand that the question was considered too academic or even quaint by the assorted realists on the commission. But I suppose that it is only this question that gave sense to the conference on which this monograph is based. Will not a science of man be appraised, eventually, by how effectively it travels a full circle, beginning and ending with this question?

Stepped down to the operable level of biology, the proposition reads: What is Man's Place in Nature? On the answer to this theoretical proposition must depend finally all our applied human biology.

The question does not stay answered, and this is the fault of science itself. For as soon as new concepts and categories of the natural world are formulated, then man himself has to be reinterpreted against the new facts and the new meanings in those facts. Thomas H. Huxley's placement of man in nature will not do today, because there is so much more nature today in which to place him. But for discussions such as this, then, we stand to lose man's place in nature by default.

Since modern biology is heavily quantified, then man the animal must also be a subject of quantification. Bioanthropologists must play Alice and run with the Red Queen of biology if we are to stay together under the same philosophical tree.

It is hopelessly beyond the scope of this publication to review the nature in which man must be placed. Nevertheless, we must measure him against something, and we must use a yardstick that can be used also on other subjects. It is within bounds, I believe, to remark that the measurement of man must come to terms with such things as feedbacks, topologies, and matrices, not because these represent techniques, but because of the concepts that lie behind any techniques they may suggest.

No less true is it that man's practical problems with himself cannot wait until he has been resolved theoretically. We must measure man now and here. Military personnel demand better footgear; civilian populations may need to be provided with gas masks; airplane cockpits must be fitted to men—not merely the other way around; artificial limbs must work; if diseases have predilections for certain bodily constitutions or other genetic patterns, we must know it. And so on.

We are not forced hereby to commit ourselves to the proposition that only what is metric is seizable. We are convinced nevertheless, I believe, that quantification is, for very many purposes, the most effective if not indeed the only way of seizing phenomena to which it is adaptable.

The 19th century anthropometry measured states: either one state only, or a succession of states between which others could be interpolated if need be. It measured distances on skeleton and living, and ratioed one measurement to another as an *index*. Essentially, this substitutes Euclidean figures, plane or solid, for the human body. The variations over a population may then be measured as deviations and correlations in geometric figures. The procedure quantifies the single trait over a population.

All this is said baldly, but not to belittle the achievements of the 19th century, for it all was an advance over what had come before. The 19th century was analytic and atomistic—for good and ill both. But the procedures, while they sharpened our focus upon details, failed to render back to us the *Gestalt*—the configuration—of man from which they took their departure. They failed to vindicate the hoary truth that the whole is greater than the sum of its parts. Von Eickstedt has said, "Detailed measurings and correlations of themselves make but an incomplete science; they are no longer analytic ends in themselves; they now serve purposely to build up a holistic notion of the individual."* Moreover, the individuals are not just posed figures. They are something that moves, something that has become, and is still becoming. Modern anthropometry must measure, not just man in repose, but man under stresses. Every motion carries stress. And whatever repose may be, stresses are variables. And now let it be said carefully that there is no intention here to suggest that old techniques be jettisoned while they are continuing to achieve valid results; but even when we use long-established techniques of measurement, we use them upon problems posed in a new way. Some of the papers in this monograph, in fact, will demonstrate this brilliantly. It remains true at the same time that today we think in terms of *process*. States are momentary abstractions of process, not merely ingredients which add up to and reflect a process, while yet the process itself remains hidden.

Characteristic of our dynamic anthropometry today is the fact that it arises from situational analyses far more than obtained in the 19th century. A situation presents facets that are at once anatomical, physiological, biochemical, psychological, and social. A situation is a practical matter. This points to the fact that, just as certainly as applied anthropometry is ultimately unsound or no more than an *ad hoc* expedient if it is not underwritten by theoretical biology, so, too, sound bioanthropological theory must have the bread and meat of practical and empirical problems if it is to be well nourished. Such a theory is a form of feedback.

Let any situation be considered. If anatomy, physiology, and so forth be taken as warp, then there is a weft that is at once ontogenetic development and phylogenetic transformation. There is genetic and environmental texture. There are theoretical and practical colors. Merely as a catalytic to our discussion, let some of these spots be touched upon lightly.

### *Growth*

The term growth is itself a catchall for a diversity of phenomena. If, however, we are thinking of those bodily changes that convert embryo into adult, then quantitatively the metamorphosis takes place by way of a regionalism. Students of growth seem to be working toward a field concept, a regionalism that cuts across the older system that measured increment in terms of, say, size changes in femur or innominate, or in a skeletal aggregate of dimensions that add up to stature. To repeat: we shall continue to have use for femoral lengths and for calendars of epiphyseal unions. Yet there is also the fact that a skull does not simply expand, incrementally, uniformly over its entirety. It does not transform in size and shape merely by way of a set of constant second derivatives. Furthermore, function is not merely something made possible by structure. Function somehow is a reciprocating partner of structure. The key words here are "somehow" and "reciprocating." There are topologies that are local yet not autochthonous, that are subordinate to some patterned control that must have unimaginable theoretical and practical import and presumably calls for multiple factor analysis, tensor calculus, transformational geometry.

---

* **Ganzheitsanthropologie.**

Speaking practically, do we know what is maximum and what is optimum growth of the individual? Would optima and maxima be related to each other identically in Whites, Negroes, Chinese? May there now be, possibly, genetic evolutionary differentia in the ontogeny of the jaws of Whites which render the problems of orthodontia either different or more acute in Whites as against Negroes? If Morant be correct in stating that the population of England reaches full stature at an earlier age than its grandparents did (and so gives the false impression that people are becoming taller), is this a good or a bad thing? What is causing it? How do you induce an *optimum* growth *rate*?

### *Phylogeny*

Central to bioanthropological thought—no matter how catholic and integrated its disciplinary provinces may ever become—remains the organic evolution of man. Evolution is, to be sure, an academic matter in its own right. Reflection, however, must show that, in the last analysis, its shape must channel our practical applications.

At least three lines of reference converge upon man's phylogeny: paleontology, genetics, and ontogeny. These three represent separate quantifications.

In the last two decades, *paleontology*, notably under the stimulation of Doctor Simpson and his colleagues, has begun to measure the *tempo and mode* of evolution; *genetics*, to calculate *rates* of mutation and genetic drift in vertebrates and man. Meanwhile, *ontogenetic* studies have begun to supply the basic quantification that some day may clarify the connections between ontogeny and phylogeny—a real problem, and still a very dark continent.

Paleontology is forced to handle almost nothing but adult remains; largely, fossilized skeletons, more or less fragmentary. But adults are end products of ontogenetic processes. The ontogenetic processes, in turn, are the products of phylogenetic processes, whatever this term may be found to mean. No adult gives rise to an adult. If we set up a phyletic series of adults—say, from Eohippus to Equus or Hipparion or any other—and measure, somehow, the degree of transformation between their levels, we are measuring the length of a hop between steppingstones, whereas actually the steppingstones landed in their places only by an integrated series of trajectories launched from the shore. The position of not one of them is determined by the one preceding it.

Analogies may be pursued only as far as their perpetrator has intended. This last one lays itself open to pressing the claim for orthogenesis. It is not so intended. Orthogenesis remains neither proved nor disproved. Perhaps something more than data is needed. Perhaps orthogenesis will remain *in statu ignoto* until a more sophisticated mathematic has been brought to bear upon it. If so, it is our legitimate concern.

Meanwhile, to step down to a more immediate level: man differs from his infrahuman ancestors in body size and shape, and in life span and the segments of that life span. And these severally are not likely to prove independent variables. They reflect alterations of ontogenetic growth rates. Do we not possess here a problem that is at once one of multiple factor analysis, differential geometry, and topological spaces? And what genetic mutations, in number, rate, and size, have so altered patterns of growth rate as to produce a man out of some ape? Do these mutations themselves constitute a process pattern?

It is not inconceivable that if we apply the techniques that these mathematic provinces represent, much that is now puzzling though fascinating about man's morphological evolution will begin to resolve itself, and in a new light. And maybe we are ready for it. To illustrate with a couple of relatively simple inductions:

First, South Africa has been yielding man-apes that are more humanlike than any extant ape, yet are not ancestral to man. *Homination* (to anglicize a Spanish term) may be viewed as a particular processual complex varyingly expressed among Primates, extinct and extant. Oddly, too, we must be ready to entertain the notion that, sometime in the Tertiary, there may have been man-apes not destined to be ancestral to man that nevertheless, at the time, were the most humanlike Primates in existence.

Second, if, instead of examining astragalus and calcaneus separately in the men of Spy, we consider them as a functioning mechanism, we shall cease to list some of their dimensional features as more apelike than modern man's, and others as human or ultrahuman. To say that Neanderthal man was "more apelike" than modern man is a comparison with about as much validity of principle, I believe, as one which would state baldly that George is more intelligent than Sadie. Just so, it does not bother us today that *Homo rhodesensis* had much more apish brow ridges than any ape ever had, or that apes have gone farther in the reduction of the mammalian tail skeleton than man has. The 19th century anthropometrist who, in his effort to atomize and pinpoint, selected from human and ape astragali single differences of size and shape, bypassed a pattern. *We* do not want placement of a trait on a scale, but location and identification of an unbounded pattern in a larger field—in this case, a multidimensional pattern of homination within the larger field of primate process.

Most of our evidence for organic evolution is morphological. With all that is known about modern man's physiology, biochemistry, psychology, and social behavior, only an astoundingly small amount has been ploughed back into evolutionary tempo and mode. Perhaps its formidable challenge is what has daunted us, although I am inclined to see in it something of historical accident. But in measure as our practical interest shifts from emphasis upon the results of evolutionary event to the processes that are evolution, perhaps we shall do better.

### *Brain*

On two counts, man is the far-left-wing member of the Primate Order: his orthogradation and his brain power. I suppose that practically all of man's peculiar problems ultimately stem from either or both of these two facts.

If we knew as much about the growth and evolution of the brain as we do about the skull or, again, as we do about the postcranial skeleton and musculature, which have to do with orthogradation, we should be fairly well off, functionally as well as morphologically. But an anthropometry of the brain hardly exists.

The import of this situation might be illustrated in many ways. One or two must be hint enough. As analogy, take the comparative anatomy of the vertebral column. On the basis sheerly of morphological features, it is possible to construct evolutionary sequences in the column. But it is only when the functional implications of the evolutionary changes begin to appear that the force and significance of the changes come out. Now turn to the brain. Its gross comparative morphology is pretty clear and, unlike the case of the vertebral column, here in man we have an unmistakable and spectacular superlative. When we consider function along with its morphology, we are confronted with the most complex single thing in the known universe. So it is not surprising that evaluation of the brain is only begun.

The gap between psychology and neurology is still uncomfortably wide. Nevertheless, I believe it not incorrect to say that the gap is narrowing rather rapidly. Moreover, the more the function of the brain is understood, the closer seems its intimacy with the endocrine system or, for that matter, with the splanchnic processes in general. This means that, in proportion as psychology becomes biology, it becomes bioanthropology and also biosociology. Between stimulus and response lies the organism itself—focally here, the human organism. It is no merely passive assorter and transmitter of stimuli, but a generator of actions. It is antientropic; it operates under feedback; it utilizes, apparently, closed circuits as booster mechanisms. Communication is a property of life. Can a proper bioanthropology do without the quantifications that are beginning to pile up in cybernetics and in the mathematical biology of social behavior? Is it true that neurologists are being attracted by the point-to-point correspondences of topology? Is projective psychology evolving an actually new conception of measurement with which psychobiology must eventually reckon?

To turn to the applied level, the situational analysis where human engineering operates, permits no separation between anatomy, physiology, and psyche:

concretely, when you are designing the lever handles and the instrument boards of an airplane cockpit, do you design them only with a condition of psychic and somatic freshness in mind, or do you have to build in a margin that takes account of some threshold beyond which there is stress or fatigue?

But before we become involved in the topic of human engineering, another comment about the evolution of the brain is timely.

In paleontology, there are numerous studies of whole phyla of mammals covering millions of years from their inception to their extinction, mammals that register the extreme species and genera as well as the more "typical." The references of comparison are in these cases intraphyletic. But if there exist any studies that have selected out the extreme members of a number of phyla, to appraise by comparisons the capacities of the several phyla to produce degrees of extremeness, then I simply do not know of such studies. Now, brain power is not a monopoly of the Primate Order, but the central tendency of that order is toward high brain power. But hold! Can we even speak of a central tendency at all in such a connection? Man represents indeed an "extreme": yes, but—an extreme of *what*? Should we not first have some precise frame of reference from which to appraise the meaning of "extreme"?

### *Human Engineering*

Five years ago, the New York Academy of Sciences sponsored a Conference on Human Engineering.* Applied dynamic anthropometry has not waited for systematized theory. The armed services have been conspicuous, though not alone, in developing it.

The issue (to repeat) is, whether you adapt man to the machine or the machine to man, or both. It is a problem of *autoecology*.

In the crude era of paleotechnics (to borrow from Lewis Mumford), there was no issue visible. Man accommodated himself to the machine, period. We biologists are sure that you cannot just do that—not with a creature whose formative, adaptive genetics took up the entire Pleistocene, whose range limits of tolerance of novel stresses are still largely unmeasured, to say nothing of optima. It has been interesting to discover, empirically, that a young adult aviator can "take" the sudden pressure of 40 G's, or even more. But if man is a configuration, then we must admit that all we have measured here is a narrow and abstracted band of that configuration. We know nothing of what successful survival of 40 G's today may mean to the whole man 40 years from now, or in what ways that meaning may express itself. At all events, we are not asking today what is optimum, but rather what limit of tolerance there may be beyond which there are immediate undesirable effects. Of course, we can learn the limits of capacity only by testing the capacity. The point of this moment is that our questions are not oriented toward promotion of welfare but toward mere survival. We have not considered what kind of questions are long-term questions.

Here an anthropometric problem becomes relevant to social biology. In the wider social sense, man must indeed continue to accommodate himself to the machine, for weal or woe, even while a particular machine is being "fitted" to him, *i.e.*, while it is being so constructed as to minimize *unuseful nonaccommodation.* Now, when an aviator loses a bout with an antagonist machine, the consequence, let us say, is loss of a limb. He is thereupon faced with the irony of adjusting to yet another machine: an artificial limb. But because we are much more concerned today that the shock of the machine shall, as far as possible, be mitigated, we are attacking more profoundly the complex dynamics of motion and stress in the *human* machine. Fulcra, pivots, axes are movables that describe curves as they move. Clearly, the old Euclidean figures that substituted for the actual relationships of human parts, and that we expressed as simple indices, have long ceased to be enough.

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* *See:* 1951. Human Engineering. Ann. N. Y. Acad. Sci. **51**(7): 1123–1278.

Finally—whither are populations headed? Demographers and social scientists cannot supply all, or as much of the answer as it is the responsibility of science to uncover. What lasting aggregate biological effects do what environments imprint upon this creature product of the Pleistocene?

In England, the biometric school sought to work out tools for attacking the problem and, in this connection, we think of such studies as Morant's on successions of Egyptian skeletons. In the United States, the pioneer—and lone wolf, I am afraid—is Doctor Angel, of Jefferson Medical College, Philadelphia, Pa.

But the *great* problem—to bioanthropologists, to all measurers of man, it will remain our $64,000 question—is almost as much of a mystery as ever. Of course it is vast and formidable, and therefore not solvable overnight. Yet may we not raise the question: Is a solution being attempted adequately? And may I suggest, diffidently, that solution lies partially in the readiness to apply new mathematical and metric techniques whose grammar and idiom permit the couching of new kinds of questions?

None of us, I am sure, was under the delusion that our two days of conferring would be adequate even for the basic topics that a catholic presentation should cover, or that this paper is an adequate introduction of what we intended to do. In point of methodology, in Doctor Ackoff's words,* we worked toward this much:

"Develop more efficient ways of investigating problems already capable of scientific inquiry;

"Develop means for scientifically investigating problems at present not capable of being investigated scientifically;

"Develop criteria by which scientific methods can be evaluated and thereby formulate principles of efficient scientific inquiry."

If we had attempted to resolve all the foregoing matters, and many others of their ilk, would we not have been reaching for the moon? Of course. And of course our reach is a little too short. Still, it is nice to know where the moon is.

All that we did can be reduced to answering two questions:

What have you who are not anthropologists to offer those of us who are?

What would you in turn like to have us furnish you?

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* Ackoff, R. L. Scientific method and social science: East and West. : 52. Soviet Sci.

# ORGANIC FORM AS DETERMINED BY FUNCTION

*By* N. Rashevsky

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The problem of organic form, especially of the form of metazoa, is one of the most difficult problems of mathematical biology. Two approaches have thus far been attempted.

The first starts with a single cell, as the fundamental unit of all living things. The problem of form of single cells appears to be much easier. It was possible to show[1] that due to interactions of forces other than surface tension, in particular due to so-called diffusion drag forces, an essentially liquid cell may possess shapes very different from the sphere. Further mathematical study of those forces led to the conclusion that they manifest themselves also intercellularly.[2]

It was therefore natural to attempt to study the effects of those forces upon the shapes of aggregates of a larger number of cells, and thus hope to arrive eventually at a theory of complex shapes such as characterize the higher metazoa. While for aggregates that consist of relatively few cells, as in the case of early embryonic stages, this approach has led to some interesting results,[3] its application to the more complex forms must be considered as a failure.[2] There is hardly anything surprising in this. In celestial mechanics, where we deal with conservative forces varying as the inverse square of the distance, the general solution of the $n$-body problem still defies the ingenuity of mathematicians. In an aggregate of cells we deal, in general, with nonconservative forces, which vary with distance in a very complicated manner. The number of cells in a higher animal is of the order of $10^{15}$. What are the chances, indeed, of successfully tackling such a problem?

Similar situations occur in the physical sciences. It is generally accepted that the physical forces that have shaped our continents are in the ultimate analysis reducible to interatomic forces between different atoms. Yet no one in his senses would attempt to explain the shapes of various continents directly in terms of those interatomic forces. A much more gross approach in terms of "macroscopic" concepts, such as continental drifts, *etc.*, is used.

A somewhat similar approach seems to be indicated in our problem, at least as a temporary expedient. We must attempt to derive the different shapes of metazoan organisms in terms of some gross, macroscopical principles.

Before we do this, however, we must solve another problem, namely, how to describe the shape of higher organisms in quantitative terms.

Any geometrical shape can be described, of course, by an appropriate equation. But such a procedure, apart from other inconveniences, would be quite useless and lack the necessary generality. No two organisms, even of the same species, are exactly alike. But a very small change in the geometric shape may require a very radical change in the equation that describes that shape. Provided a great deal of effort, it may be possible, for example, to describe by an equation the profile of a contour of a dog, standing, let us say, with its tail down. But let the dog wiggle its tail, and what happens to your equation?

There is, however, no need for such an exact description, because of the above-mentioned dissimilarity of even closely related organisms. Consider, for example, a tree, and let us specify approximately the average diameter and the height of its trunk, as well as the average number, average length, and average diameter of its primary branches. Even such a crude description gives us a general idea of the shape of the organism. For example, if we say that the trunk is 25 cm. in diameter and 150 cm. long, the number of primary branches is 5, their average length 300 cm., and their average diameter 15 cm., we then find a shape somewhat like the one shown in FIGURE 1. If, on the other hand, we say that the diameter $2r_0$ of the trunk is $2r_0 = 75$ cm., its length $l_0 = 900$ cm., the number $n$ of primary branches is $n = 11$, their diameter $2r = 15$ cm., and their length $l = 600$ cm., we find a shape similar to that shown in FIGURE 2. With $2r_0 = 60$ cm., $l_0 = 950$ cm., $n = 200$, $2r = 1$ cm., and $l \doteq 50$ cm., we find a shape like that shown in FIGURE 3. Those shapes are not yet sufficient to identify the tree in question. But no one would mistake the tree of FIGURE 1 for an oak or a poplar. It may be a small apple or pear tree. On the other hand, FIGURE 2 may represent an oak, maple, beech, or the like, while FIGURE 3 may be a poplar or a tall juniper. A complete identification would require additional data such as number and size of secondary branches, number of leaves, length and width of leaves, or even their gross shape. But the latter can again be described by specifying the number and depth of the lobes of the leaf. The important thing is that even a complete identification requires a *finite set of numbers that specify the approximate sizes of different parts of the organism.*

Similar considerations hold for animals. As an example, consider the quadrupeds. Specifying the average length of the body as 350 cm., the average width of the body as 220 cm., the diameter of extremities as 50 cm., and their length as 250 cm., we may imagine an elephant, a hippopotamus, or a rhinoceros. But no one will think, in terms of those specifications, of a giraffe or a dachshund. Here, again, a finite set of figures that gives the approximate sizes of different parts of the body may specify sufficiently the gross shape of the animal.

Having thus decided on a method of giving a *practical* description of the shapes of organisms in quantitative terms, we may now pass to our principal problem; namely, to derive the different existing shapes of plants and animals from some general quantitative postulate or principle.

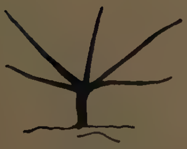

FIGURE 1.

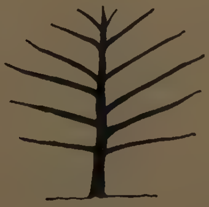

FIGURE 2.

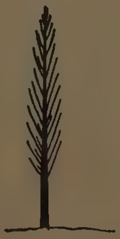

FIGURE 3.

Every living organism performs a large number of different biological functions. Those functions may be of a great variety. Every organism, plant or animal, metabolizes a large number of substances, thus performing metabolic or biochemical functions. To obtain from outside those metabolites, the organism performs more or less complicated intake or feeding functions. Similarly it performs eliminative functions. An animal has to seek out its food in different places. It must be able to chase its prey, if it feeds on other animals, and/or to run away from another animal which feeds on it. To that end, an animal performs complicated locomotory functions.

In addition to this, the organisms must perform some purely mechanical functions. A tree must be strong enough not to be broken by the average prevailing winds. It also must be strong enough not to collapse under its own weight. The legs of a quadruped must be strong enough to support the weight of the body, *etc.*

Let us suppose that the functions of a given organism are specified as to their number and intensities. We may ask ourselves, then, how an organism may be "designed" so as to fulfill all those functions. The total number of possible designs is infinite. But if we impose the condition that the design be the simplest one possible and the most economic as to the amount of available material, it is quite possible that the number of possibilities will narrow down to a few, or even a single one.

We may formulate the whole problem somewhat differently, namely, thus: If an engineer had to design a mechanism that must perform certain prescribed functions, how would he choose the best possible design? Such a design will obviously determine the sizes of various parts of the organism, and, therefore, its gross shape.

This approach seems at first to be rather anthropopsychic, almost implying the existence of a personal designer or creator. This, however, is not so. The "best" designs have a better chance of survival in the struggle for existence. Therefore, during the millions of years of development of the organic world, natural selection would have left only the "best designed" organisms for our study.

In order to see whether the above principle can lead to any useful results, we must try to apply it to some simple cases. As in any early theory, the cases need not be necessarily very realistic. They may serve mainly the purpose of showing what can be done with a given principle. Our first illustration will be of such a none-too-realistic nature. Later on, we shall discuss the work of David L. Cohn, in which a considerably more realistic application of this principle, which he calls "optimal design," is made.

Let us first consider the plants, and restrict our specification to the quantities $r_0$, $l_0$, $n$, $r$, and $l$. Consider a plant with a given total mass $M$. If $\delta$ denotes the average specific gravity or density of the plant, we have the approximate relation:

$$M = \pi\delta(l_0r_0^2 + nlr^2) \tag{1}$$

Every plant metabolizes a very large number of substances at different rates.

In our idealized nonrealistic model, we shall introduce a fictitious average rate $q$ of metabolism, per unit mass. Since the leaves may be considered as the principal seat of metabolism, therefore the total metabolism $qM$ may be approximately set proportional to the total number of leaves. The latter, in its turn, may be very roughly set proportional to the total surface of the primary branches. Thus, with $k$ as a constant of proportionality, we have roughly

$$qM = knlr \tag{2}$$

From mechanical considerations, the length of a branch cannot exceed a certain value, determined by its radius, lest the branch break under its own weight. Therefore, the length $l$ is some function $f(r, \delta)$, since $\delta$ affects the mechanical strength of the branch. Thus

$$l = f(r, \delta). \tag{3}$$

Similarly, from considerations of strength, there is a relation between $l_0$, $r_0$, $\delta$, and $M$, which may be written

$$l_0 = f_0(r_0, \delta, M) \tag{4}$$

The total flow of metabolites through the trunk is limited by $r_0$, and the diffusion properties of the material, which depend, among other things, on $\delta$. If $r_0$ is chosen, from economic considerations, just large enough to permit the necessary flow, we have for the trunk the relation

$$r_0 = f_1(qM, \delta) \tag{5}$$

and a similar relation for each branch

$$r = f_1\left(\frac{qM}{n}, \delta\right) \tag{6}$$

Altogether we have six equations, from which the quantities $r_0$, $l_0$, $n$, $r$, $l$, and $\delta$ can be expressed in terms of $q$ and $M$. But the first five quantities determine, as we have seen, the gross shape of the plant. Thus basically, we see that such consideration *can* lead to a theory of the shape of the plants.

Making some simple and not too plausible assumptions about the functions $f$, $f_0$, and $f_1$, it was possible to show[4] that for different values of the parameters $M$ and $q$, we do obtain the three shapes shown in FIGURES 1, 2, and 3, together with intermediate forms.

We emphasize again that all this is to be considered only as an illustration, which shows that the principle of optimal design can lead to a description of the form of plants. Further generalizations and complications have been suggested. Thus instead of equal branches, we may introduce a distribution function $n(l)$ such that

$$\int_0^\infty n(l)dl = n,$$

and determine $n(l)$ from considerations of optimal design.

A generalization has also been outlined[5] to take into account branches of higher order, as well as the size and shapes of leaves. Interesting studies on the relation of mechanical properties of trees to their form have been made by I. Opatowski[6] and M. H. M. Esser.[7]

In passing now to animals, we shall mention only one very crude illustration, taken from a larger number of those that have been studied.

The body, the trunk of a quadruped mammal, is supported at its ends by the four extremities. Clearly, if the body, for a given total mass, would be very long but narrow, it would sag in the middle, and, when a certain ratio of length $L$ to width $W$ is exceeded, it may sag so badly as actually to drag its middle on the ground, and make not only the locomotion, but even the performance of other functions, impossible. The mechanical structure of the animal trunk is very complicated. While one of its main supports comes from the spine, yet the ribs as well as the musculature contribute to its rigidity. A complete mathematical theory of the mechanical strength of such a complicated system is now quite out of the question. Let us, however, just out of curiosity, see what happens, if we assume that the trunk of an animal behaves mechanically, like a solid bar of length $L$ and width $W$, supported at the ends. We then may use the following approximate argument.

If such a bar is uniformly loaded with a load $p$ per unit length, then the sagging $f$ in the middle is

$$f \propto \frac{pL^4}{W^4} \tag{7}$$

hence the relative sagging is

$$\frac{f}{L} \propto \frac{pL^3}{W^4} \tag{8}$$

By definition

$$p = \frac{M}{L} \tag{9}$$

where $M$ is the mass of the trunk, which may be set approximately equal to the total mass of the animal. Hence

$$\frac{f}{L} \propto \frac{ML^2}{W^4} \tag{10}$$

The relative sagging should not exceed a certain threshold, lest the bar break. Assuming this threshold to be constant, and that $f/L$ is always a given fraction of that constant, we have

$$\frac{ML^2}{W^4} = \text{constant}, \qquad \text{or} \qquad \frac{L^2}{W^4} \propto M^{-1} \tag{11}$$

We have approximately

$$LW^2 = M. \tag{12}$$

EQUATIONS Nos. 11 and 12 give

$$L \propto M^{1/4}; \qquad W \propto M^{3/8}; \qquad \frac{L}{W} \propto M^{-1/8}; \qquad W \propto L^{3/2} \qquad (13)$$

Thus, with increasing mass of the animal the trunk becomes shorter relative to its length.

Of course we cannot expect relations (EQUATION No. 13) to hold exactly. It is, however, very interesting that within the range from cat to ox, the relation $W \propto L^{3/2}$ holds roughly, as seen from FIGURE 4, where $W$ is plotted against $L$ on logarithmic scale.

The ratio $W/L$ does determine partly the over-all shape of the animal, and thus we see that again we can obtain relations that describe the shape of animals from the principle of optimal design.

It has been shown that the required speed of locomotion is a determining factor for the length of the extremities, while the total mass of the animal is a determining factor for the diameter of the extremities.[8] The crude theoretical relations obtained have shown a much worse agreement with available, unfortunately also very crude, data, but the trends are correct. Thus in principle the possibility of deriving the gross external shapes of organisms from considerations of design may be said to have been established.

We may, of course, ask the more fundamental question: Why do some animals have four extremities, some none, some more than four? The answer to that question may also be thought of in the principle of optimal design. Kinematically all animals may be considered as complex systems of *linked levers*. The locomotory properties, as well as other functions connected with relative move-

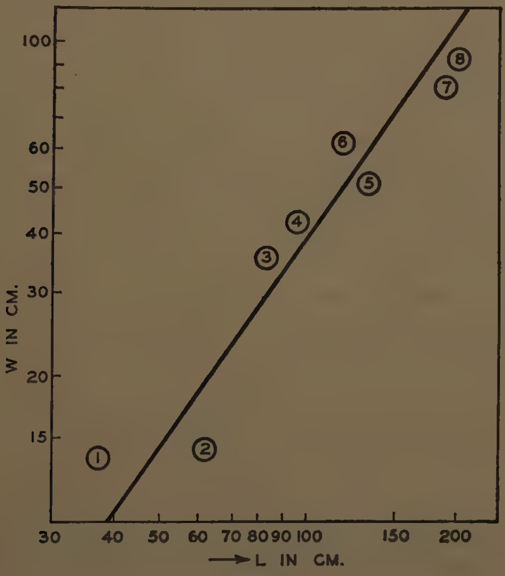

FIGURE 4.

ments of different parts of the animal body, are closely related to the dynamics of such systems of linked levers. The general mathematical theory of such systems leads to complicated nonlinear differential equations, and very little mathematical progress has yet been made in this direction. Using, however, some crude approximations, some conclusions may be drawn that throw light upon such questions as the number of extremities, number of links in an extremity, *etc.*[8]

We may now go a step further and not limit ourselves to the external shape of animals. If, from considerations of optimal design, we can derive the sizes of some internal organs, we to some extent thereby also describe their shape. For example, if we find that in an animal with body length of 5 cm. the intestinal tract is 10 cm. long while, in another animal with a body length of 25 cm., it is 200 cm. long, we shall rightly conclude that the intestines of the second animal are much more folded and looped than in the first. But this is a statement about the shape of the intestinal tract.

Crude considerations, involving the amount of oxygen necessary to provide the needed energy for an animal of given mass have led to some relations between the size of lungs and of the heart and the total mass of the animal. The mass of the lungs and that of the heart should be proportional to the total mass of the animal, a relation that is very crudely satisfied so far as the meager data can show.[9] The theory also requires that the frequency of respiratory movements, as well as the frequency of heart beat, should vary as the inverse cubic root of the mass of the animal. FIGURE 5 shows to what extent those relations are actually observed. Here the frequency $\nu_L$ of breathing is plotted against the mass $M$ of the animal on logarithmic scale. The range is from a rat to a horse.

We shall now discuss the recent, partly as yet unpublished, work of David L. Cohn,[10, 11] in which he has applied the principle of optimal design to the structure of the vascular tree. The results obtained here are considerably more realistic and accurate.

Cohn begins by discussing the radius of the aorta. For a given total blood

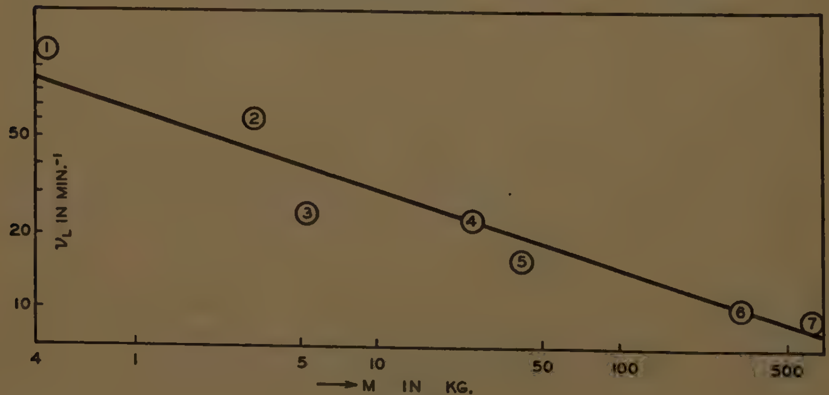

FIGURE 5.

flow, determined by the metabolic requirements of the organism, a smaller aorta means a saving of material available for the vascular system. As the radius decreases, however, the resistance increases, and, for given properties of blood, the Reynolds number will become critical, with turbulance setting in, and further increase of resistance. Hence we may argue that the best size of the aorta is that below which the Reynolds number becomes critical.

Let $C$ be the total flow in cm.$^3$ sec.$^{-1}$. Then, if $r_A$ is the radius of the aorta, the average velocity of flow $\bar{v}$ is given by

$$\bar{v} = \frac{C}{\pi r_A^2} \tag{14}$$

The Reynolds number $R$ for a fluid of viscosity $\eta$ and density $\delta$, flowing through a cylindrical vessel of radius $r_A$ with a velocity $\bar{v}$, is given by

$$R = \frac{\delta \bar{v} r_A}{\eta} \tag{15}$$

which gives

$$r_A = \frac{\eta R}{\delta \bar{v}} \tag{16}$$

Substituting EQUATION No. 14 into No. 16, we find

$$r_A = \frac{\delta C}{\pi \eta R} \tag{17}$$

The critical value of the Reynolds number for blood is about 1100. Hence the optimal size $r_A^*$ of the aorta is given by

$$r_A^* = \frac{\delta C}{1100 \pi \eta} \tag{18}$$

Next, Cohn considers the capillaries. Their diameter is essentially limited by the size of the red blood cells. Their length must be such that blood stays long enough in each of them to allow for a proper diffusion exchange with the external medium. Similar considerations of diffusion, into which we cannot here go into detail, determine the volume of tissue to be supplied by a single capillary.

The next problem is the branching of the vascular system. In his first paper,[10] Cohn used the following argument, which in some respects seems not too realistic.

He considers a cube of tissue, the length of the edge of which is $L$. Let a cylindrical tube enter the cube in the middle of a side, perpendicular to it, and reach the center of the cube, at which point it branches in two, each branch directed at right angles and parallel to an edge of the cube, as shown in FIGURE 6. The next branching is done as shown in FIGURE 7, and the next as in FIGURE 8. In the latter figure the cube is divided into eight cubes, each with the side $\frac{1}{2}L$, and with each of those cubes we may repeat the process again. Thus to supply a cube of volume $(\frac{1}{2}L)^3$, three successive branchings of the vascular system are necessary. To supply a cube of volume $[(\frac{1}{2}^l)L]^3$, $3l$ branchings are needed. By such considerations, we can estimate the total number of branchings necessary to supply a volume, determined previously by diffusion considerations.

Anatomically, the types of blood vessels are sometimes classified by the parts of the body which they supply (pulmonary artery, femoral artery, *etc.*). In the idealized picture of the "equivalent" cube we may classify the types of blood vessels by the volume of the partial cube that they supply. Thus the vessels supplying a cube of volume $(\frac{1}{2}^i L)^3$ would be considered as belonging to the $i$th class. If there are altogether three $l$ branchings, there are $l$ classes of blood vessels, with this definition.

The abstract approximation of the complicated shape of an animal by a cube is unrealistic. In a subsequent paper,[11] Cohn has considered a more realistic case in which the major vessels all arise from a number of secondary branchings rather than from successive equal branchings of the aorta. Curiously enough, the final result comes out the same.

Finally, Cohn considers the relation between the radii of two branches of a vessel and the original vessel. If we wish to minimize the resistance of the

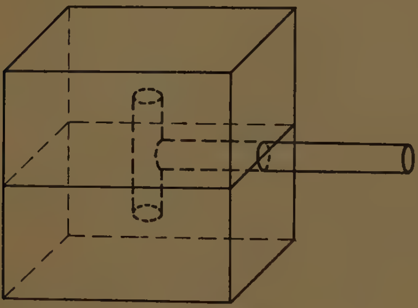

Figure 6.

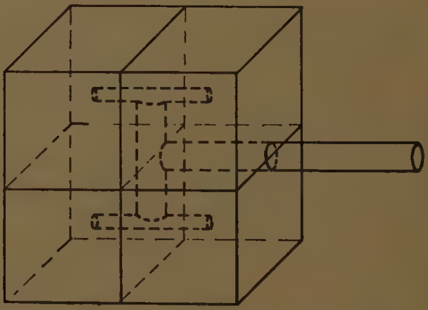

Figure 7

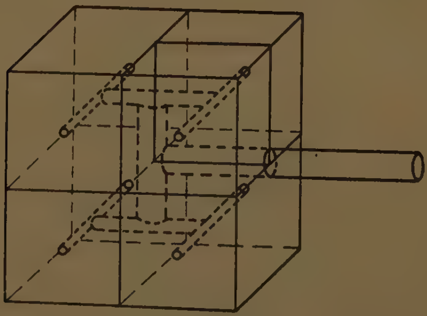

Figure 8.

system and if we have an unlimited amount of material available from which the system is built, then the proper thing to do is to make the branches of the same diameter as the original vessel. Since, however, the amount of material available is limited, and may be considered as prescribed, it is found by somewhat elaborate, but otherwise simple, mathematical considerations that there is an optimal ratio of the radius of the branches to the radius of the original vessel. This ratio is calculated to be equal to 0.794. Actually, it is found that for different branchings this ratio is rather constant and equal to 0.8, a remarkable agreement.

We have remarked above that the diameter of the capillaries is limited by the size of the erythrocytes. But it is also determined from the above considerations on branching, if, from diffusion considerations, we can calculate the maximum volume that must be supplied by a capillary. For this volume determines the number of divisions of the original cube, hence the number of branchings of the blood vessels. The latter, together with the ratio 0.794 of the radii at each branching, gives us the radius of the capillaries.

If we know the total mass of the animal (its density being practically equal to 1), then we know the side of the original "equivalent" cube. Having computed, from diffusion considerations, the volume to be supplied by a capillary, we can compute the total number of branchings between the aorta and the capillaries. If, in addition, the total cardiac output $C$ of the animal is known, we can compute from EQUATION No. 18 the radius of the aorta and, from the already computed number of branchings and the branching ratio 0.794, the diameter of the capillary. Diffusion considerations provide us then also with the length of the capillary.

Cohn applied those considerations to the case of a dog weighing 13 kg., for which data have been collected by H. G. Green.[12] The cardiac output of the dog was 40 gm. sec.$^{-1}$. The side of the "equivalent" cube of weight 13 kg. and density 1 is about 23 cm. Owing to the compactness of the idealized "equivalent" cube, however, which is not reflected in the actual organism, Cohn considers the equivalent cube as having a side of 40 cm. This value is the approximate average of the side 23 cm. of the idealized cube, and of the actual trunk length (*ca.* 60 cm.) of a dog of that weight. The following table gives a comparison of calculated and observed values:

| | *Calculated* | *Observed* |
|---|---|---|
| Radius of aorta | 0.43 cm. | 0.5 cm. |
| Ratio of radii of branches to that of the original vessel | 0.794 | 0.8 |
| Number of classifications of arteries | 11 | 9 |
| Diameter of capillaries | 2.2 $\mu$ | 4 $\mu$ |

Thus a rather complete and fairly accurate specification of the general shape of the vascular tree is obtained from the knowledge of the mass of the animal and the total cardiac output.

It is interesting that this approach to the theory of organic form suggests the possibility of using methods developed in an entirely different science, namely, econometrics. Cohn points out that in the problems of optimal design of organisms, questions of optimal supply of certain metabolites or hormones from sources, the distribution of which is given, frequently arise. Sometimes the biological problems of this type have a remarkable formal analogy with transport and supply problems, which have been successfully treated in mathematical economics. We may well witness here a cross-fertilization between two different exact sciences, a phenomenon which has always marked a milestone in scientific progress.

A well-developed mathematical theory of organic form is a goal still far removed. But in what we have discussed above, everything indicates that an approach to the problem of organic form from the point of view of engineering design is likely to lead to fruitful results.

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### *Discussion of the Paper*

Doctor H. A. Gordon (*Lobund Institute, Notre Dame, Ind.*): Under pathological conditions, in some organ functions there might be a reversible or permanent departure from the principle of economy and simplicity mentioned by the speaker. Such changes can be dictated by the need of defensive functions whose activation, though expedient in an emergency, are detrimental to economy. In terms of bacterial stress, the germfree animal permits the study of undisturbed functions throughout the course of life. In comparison, the conventional animal presents certain aspects which are apparently conditioned by the life-time association with the normal bacterial flora and which may represent a departure from the original functional economy. This is suspected to be the case, among others, in some bacterium-harboring organs where the deterioration of the capillarization becomes more manifest with advancing age. The approach presented by the speaker may help in a better understanding of the role that environmental agents play in the economy of the organism.

# ENTROPY AND GROWTH OF AN ORGANISM

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When a physicist speaks of biology, the audience must excuse his shortcomings. Nevertheless, it seems interesting to discuss how physicists and biologists can work together, and where they happen to meet on common ground.

Thermodynamics is one of the oldest chapters in physics. Its general rules and principles apply throughout all of physics and chemistry. How can these rules and principles be used in biology, and how far do they reach?

Let us first summarize the viewpoint of a physicist. He considers a closed system, completely isolated from its surroundings, and states two principles: (1) the energy of the system remains constant; and (2) a quantity called "entropy" increases, or, at best, may remain constant. The second principle (Carnot) was characterized by Lord Kelvin as indicating "degradation of energy." High-grade energy (mechanical power) has a tendency to be transformed into low-grade energy (heat). The grade of the energy can be defined as the negative entropy (negentropy), a quantity that, by the second principle, must always decrease in the normal evolution of a closed system.

A living organism is a stable system, but not a closed one. We may enclose the organism in a cage, provide it with food, and investigate its life in confinement. It uses the food, produces work, and leaves all sorts of refuse. The general principles stated above indicate that, while the total energy remains unchanged during this process, the entropy must increase. Assuming an adult organism to maintain, at least approximately, a stable state, we thus say: entropy of food is smaller that entropy of refuse or, in other words, an organism feeds on negative entropy.[1] The problem sketched here is precisely the problem of metabolism. It would be much easier to discuss if we could speak of the entropy of the living system itself, but we cannot do so.

In a private discussion at Harvard University (1948), P. W. Bridgman presented the argument in a very precise way. He said, in effect, that in order to define the entropy of a chemical system, we must be able to find a reversible chain of reactions by which this system can be derived from another one, of known entropy. But the creation or destruction of an organism cannot be realized in the laboratory in a reversible way. Birth and death are irreversible processes. Hence, the entropy of an organism cannot be defined.

Thus, the operational viewpoint of Bridgman leads to the conclusion that one should not speak of entropy for living systems.

A living system is a stable open system. It can be compared to a flame. Much research has recently been done on open chemical systems, and many important results have already been obtained by Prigogine, Onsager, H. Callen, de Groot, L. v. Bertalanffy, and M. Biot, among others.[2] The following general principle has been stated by Prigogine: a stable open system, maintained by irreversible processes, assumes a structure corresponding to minimum entropy increase. This important statement was recently discussed by M. Biot.[3]

Another recent extension of thermodynamics has taken place in the direction of the new theory of information. It has been found possible to give a scientific definition of the word "information," and to show that information is synonymous with negative entropy. From study of a physical system, it can be shown that entropy measures the lack of information about the detailed structure of the system. It is a fact that we can never know exactly where all the atoms of a gas are located. This lack of information means that there is an apparent disorder in the detailed organization of the system, and this is, essentially, what entropy measures. The reader interested in these problems will find them completely discussed in a book by the author.[4]

If information is negentropy, so also is organization. An organized structure is one about which we have complete information. It has a larger negentropy than a disorganized system. Now we begin to see the connection with life. A living system is organized. If we can define and measure its degree of organization, we may be able to define the negentropy characteristic of the living organism. This has not yet been done in a systematic way, but it does not sound impossible. The classical definition of entropy cannot be used (Bridgman), but the informational definition may apply.

Let us consider the growth of an organism from a fertilized egg. All the information about the living system is contained in the chromosomes. It is there in an abridged code, and determines the future development of the entire structure of the living organism. If we could decipher the code represented by the chromosomes, we could predict the detailed structure of the adult organism. The whole negentropy of the final organization is contained in the fertilized egg.

But is it possible to read out the information without destroying the egg? N. Bohr has repeatedly emphasized the fact that there is a special uncertainty principle applicable to all living organisms, *i.e.*, that it is impossible to make complete measurements on an organism without killing it. We cannot determine the complete chemical structure of a cell without destroying it. No scientist has yet been able to state precisely what this limitation means, but it certainly exists, and we shall have made great progress when we can see exactly how to define it.

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# D'ARCY W. THOMPSON'S MATHEMATICAL TRANSFORMATION AND THE ANALYSIS OF GROWTH

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In 1915 D'Arcy Wentworth Thompson (FIGURE 1) compared the shapes of related adult organisms by means of transformed coordinates and, in 1917, he elaborated the method in the final chapter[35-37] of his masterful work, *Growth and Form*. The resulting spectacular diagrams created interest and soon appeared in other books. It is my pleasant task in this paper to review Thompson's work with respect to current problems and developments.

## *Thompson, 1915, 1917, 1942*

The starting point, in D'Arcy's own words, is, "We begin by describing the shape of an object in the simple words of common speech: we end by defining it in the precise language of mathematics; and the one method tends to follow the other in strict scientific order and historical continuity." Growth and form, he believed, were of composite nature: therefore, the laws of mathematics are bound to underly them, and mathematical methods were believed peculiarly fitted for their interpretation. Although he remarked, "Nor must we forget that the biologist is much more exacting in his requirements, as regards to form, than the physicist; for the latter is usually content with either an ideal or a general description of form, while the student of living things must needs be specific," nevertheless he was very well aware of the importance of statistical methods for the study of variation.

Thompson states, "In a very large part of morphology, our essential task lies in the comparison of related forms rather than in precise definition of each; and the *deformation* of a complicated figure may be a phenomenon easy of comprehension, though the figure itself have to be left unanalyzed and undefined. This process of comparison, of recognizing in one form a definite permutation or *deformation* of another, apart altogether from a precise and adequate understanding of the original 'type' or standard of comparison, lies within the immediate province of mathematics, and finds its solution in the elementary use of a certain method of the mathematician. This is the Method of Coordinates, on which is based the Theory of Transformations." (Italics his.) The method was not new. In fact, Thompson publishes diagrams taken from Dürer (17th century) which compare differently shaped human heads. He was also aware of the fact that the transformations with methods at his disposal were limited to closely related organisms, and he stated the impossibility of transforming the outline of a beetle into that of a cuttlefish. Thompson believed his method appropriate for the study of evolutionary change, which he illustrated with a number of transformations.

Thompson's simplest illustration of a transformation starts with the plot of a circle on equally spaced rectangular coordinates. When the units of the $x$-axis are reduced by half, the circle is compressed into the shape of an ellipse with a vertical axis.

FIGURE 1. D'Arcy Wentworth Thompson. New Haven, Conn., 1936.

For his first biological example, Thompson drew the outline of the cannon bone of an ox within a rectangular coordinate system which he then deformed by substituting $2x/3$ for $x$. The outline in the new coordinates closely resembles the cannon bone of sheep. The further transformation, by substituting $x/3$ for $x$, produces the outline of the comparable bone of the giraffe.

The second type of transformation proposed by Thompson was a percentage transformation from substituting log $x$ for $x$. Thompson had already used the logarithmic spiral in the analysis of the shape of shells.

The third type of transformation was that of shear, wherein one axis was rotated with respect to the other, or, a function such as $c - n \cot w$ was substituted for $x$.

The fourth method was to use radial coordinates and to alter the radial and tangential velocities corresponding to an asymmetric growth. The begonia leaf illustrates this type of a transform pattern. Thompson also used polar coordinates and combined polar coordinates with harmonic motion. Transformations in three dimensions were possible, although this work was left for others to do.

Probably Thompson's most spectacular illustration was the transformation of the outline of the porcupine fish into that of the sunfish (FIGURE 2). To accomplish this, he deformed the vertical coordinates into a system of concentric circles and the horizontal coordinates into a system of curves that are

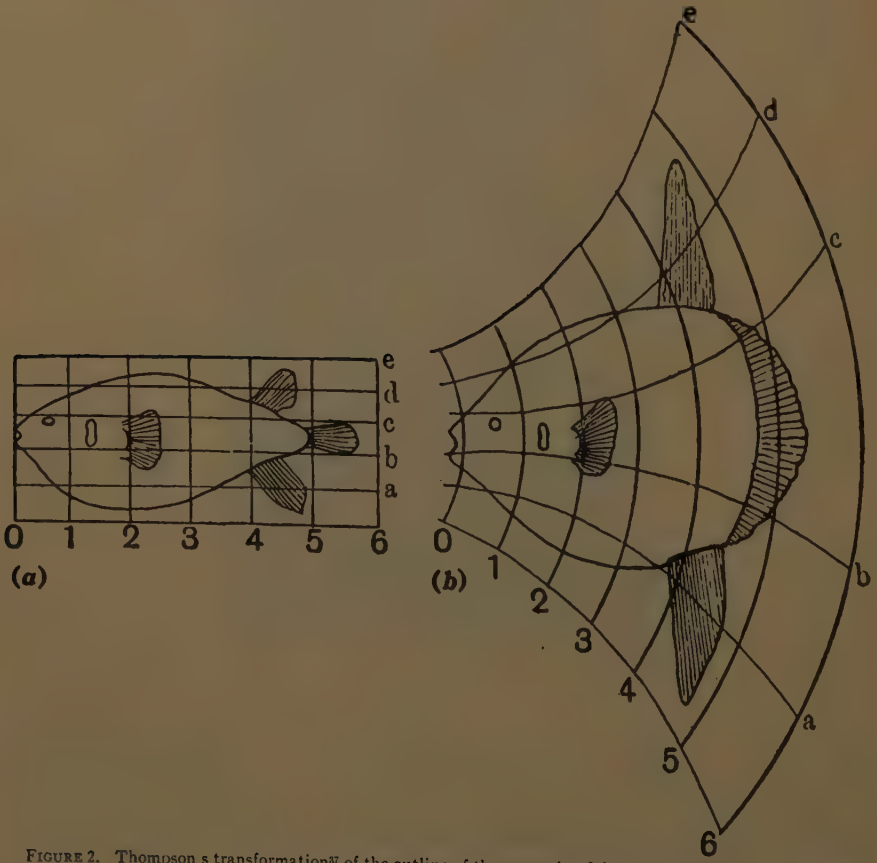

FIGURE 2. Thompson's transformation[37] of the outline of the porcupine fish (*Diodon*) into that of the sunfish (*Orthagoriscus*).

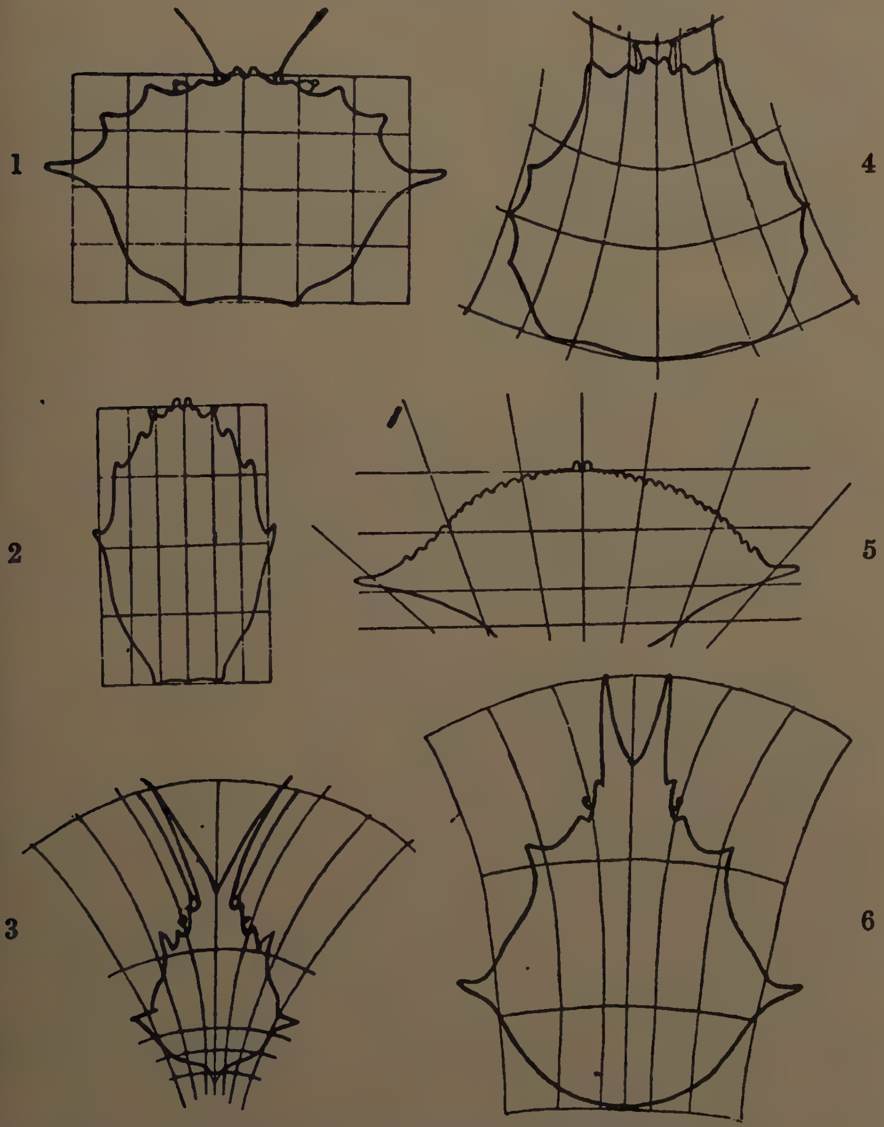

FIGURE 3. Thompson's methods for coordinate transformation[37] illustrated by the carapace outlines of crabs. (1) *Geryon*, (2) *Corystes*, (3) *Scyramanthia*, (4) *Paralomis*, (5) *Lupa*, and (6) *Chorinus*.

approximately hyperbolas. This figure appeared in a number of biological books shortly after the publication of *Growth and Form* in 1917. One of the best illustrations of Thompson's methods (FIGURE 3), shows the transformations of the carapace outline of one crab into the outlines of others.

Closer to us is his transformation of the outline of the human skull into outlines of the skulls of the chimpanzee, ape, and baboon (FIGURE 4). Thompson

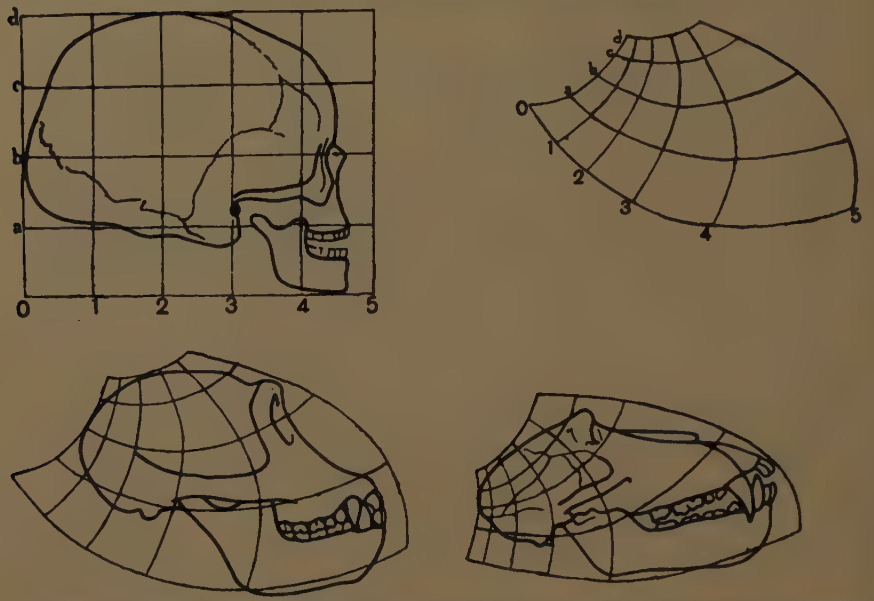

FIGURE 4. Thompson's transformations[37] of the human skull outline (upper figures) into those of chimpanzee and baboon.

states, "After easily transforming our coordinate diagram of the human skull into the corresponding diagram of an ape or a baboon, we may effect a further transformation of man or monkey into dog no less easily; and we are thereby encouraged to believe that any two mammalian skulls may be compared with, or transformed into, one another by this method. There is something, an essential and indispensable something, which is common to them all, something which is the subject of all of our transformations, and remains *invariant* (as the mathematicians say) under them all. In these transformations of ours every point may change its place, every line its curvature, every area its magnitude; but on the other hand every point and every line continues to exist, and keeps its relative order and positions throughout all distortions and transformations." (Italics his.) Thompson mentioned, of course, the fact that one could have started with curvilinear coordinates for the skulls of the lower animals and *rectified* them to obtain the outlines of the human skull!

The advantage of using all the points of the pattern is stressed in his statement, "From this comparison of the gorilla's or chimpanzee's with the human skull we really realize an inherent weakness that underlies the anthropologist's method of comparing skulls by reference to a small number of axes."

Clearly stating the limitations of these methods, Thompson says, "We *cannot* transform an invertebrate into a vertebrate nor a coelenterate into a worm, by any simple and legitimate deformation, nor by anthing short of reduction to elementary principles." Transformations therefore may be limited by Spencer's principle of discontinuity and, conversely, the limitations of transformations in practice should help reveal any discontinuities in phylogeny.

Thompson spent the World War II period in revising *Growth and Form*, but the new edition[37] of 1942 adds little to this chapter of the first edition. His method was extended to markings, such as the stripes and patterns of zebras. One obtains the impression that Thompson was a little disappointed in that transformations did not explain evolution, that 80 years of Darwinism had not "... taught us how birds descended from reptiles ..." *etc.* Geometry, on the other hand, emphasizes the discontinuities and favors explanation by mutations. The mathematical limits of transformations implied for Thompson "... a *classification* of mathematical forms, analogous to the classification of plants or animals in another part of the Systema Naturae."

Is Thompson groping here toward a biological "exclusion principle"? Is this the naturalist's language of his time for indeterminancy? Thompson expected no quick solution. When he visited Yale University in 1936, he assured me that he believed mathematical methods to be the most promising path for biological scientists. His epilogue states: "And while I have sought to shew the naturalist how a few mathematical concepts and dynamical principles may help and guide him, I have tried to shew the mathematician a field for his labour—a field which few have entered and no man has explored. Here may be found homely problems, such as often tax the highest skill of the mathematician, and reward his ingenuity all the more for their trivial associations and outward semblance of simplicity."

## *Early Applications, 1935–1937*

The transformations of Thompson were discussed in many biological seminars in the early 1920's, yet for years no published results using his method have been found. Perhaps this is partly due to Thompson's failure to provide detailed how-to-do-it instructions, and partly to the fact that relatively few copies of the first edition of his book were published. The book was practically unobtainable toward the end of the 1920's. Thompson enumerated a number of reasons why his methods would only slowly come into use. As he predicted, some biologists found mathematical methods and distinctions too difficult for taxonomic and morphological problems. Evolution theory was no longer the prime concern of biologists.

The first application of transformed coordinate analysis seems to have been made in 1935 by Colbert[9] on the Siwalik mammals. The possible evolution of the Rhinoceros skull through *Gaindatherium*, from a primitive form such as *Caenopus*, is shown in FIGURE 6.

It has seemed to me that the transformed-coordinate method would be more useful for the investigation of the development of an individual organism than for the comparison of adult forms. The fortunate availability of Blount's outline figures of developing *Amblystoma punctatum*,[3] and the interest of G. A. Riley, one of our graduate students at Yale, made possible in 1936 what we believe was the first application of Thompson's methods to ontogeny.[31] The outlines of the salamanders were enlarged by projection to a given length. Moduli, as percentages, were then calculated for 10 positions on each animal at each stage. The spacing of the coordinates at each stage was brought into

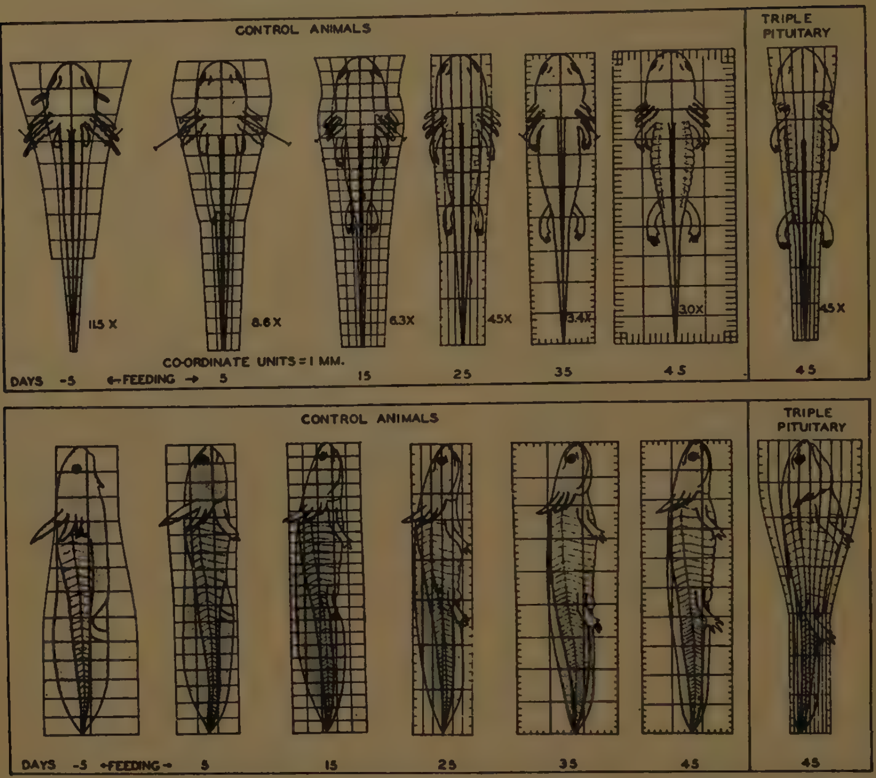

FIGURE 5. Richards and Riley's[31] transformations showing the development of salamanders from Blount's data.[3]

correspondence with the coordinates of the oldest reference stage, and fractional millimeter inequalities were arbitrarily adjusted. The changes in growth proportions from stage to stage are shown in FIGURE 5. The triangular coordinate system for the youngest stage shows early concentration of growth activity in the head region. Later, the greatest growth is in the tail region, and the coordinate changes show the decreasing activity of growth. The animal at the right, with extra pituitary glands, reveals a peculiar combination of mature and immature form in the same individual.

DeConinck[10] used transformations in 1936 to assist in defining the limits for variation separating one taxonomic species from another, although his study was primarily of the allometric growth of the unequal terminal segments of two species of nematodes.

### *Allometry*

Another active area in growth studies investigated the growth of parts of an organism with respect to growth of the whole organism. Fishery biologists were concerned with weight or volume in relation to length. Weight is rarely exactly equal to the third power of length, or other linear measurement, a fact that called attention to problems of changing form, specific density, *etc.* The "Cube Law" gave a more useful index of the condition of fish than an index of growth, and it is applied in the regulation and conservation of fisheries.

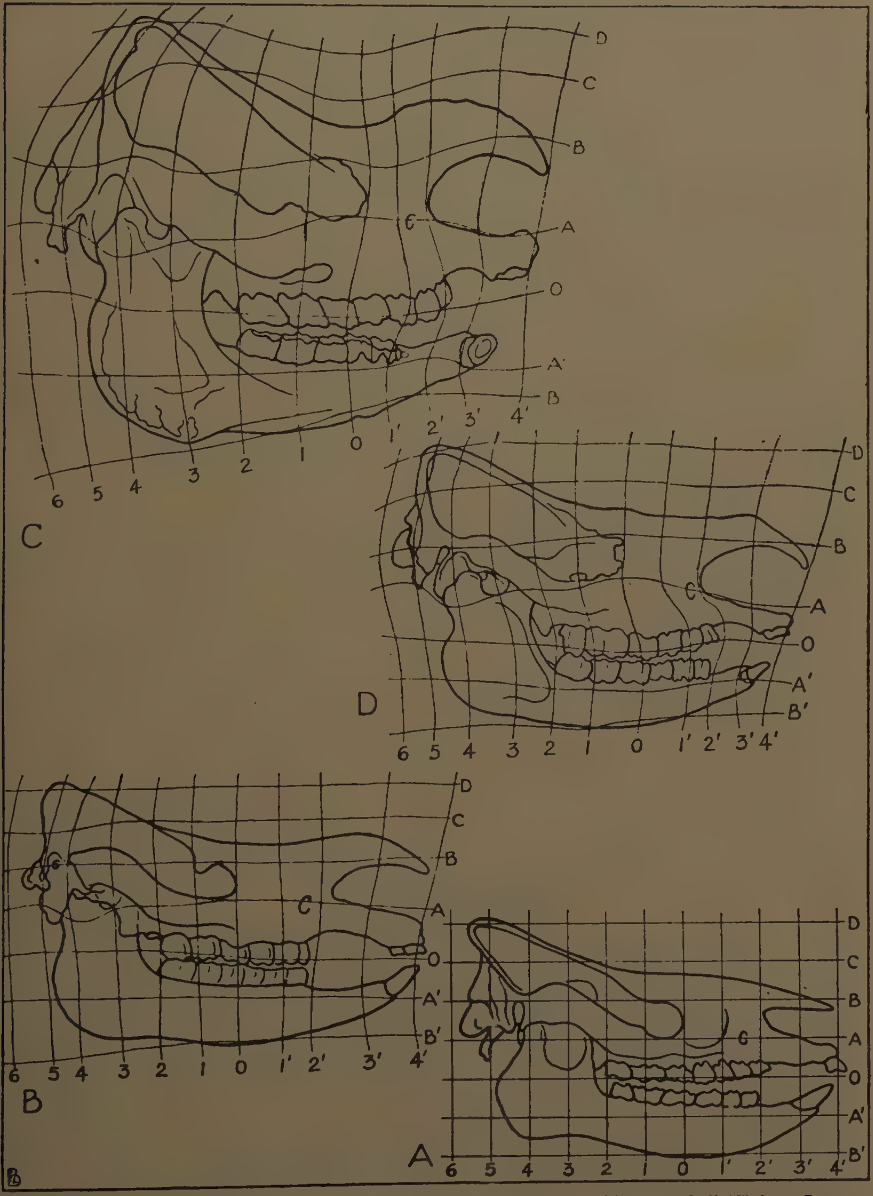

FIGURE 6. Colbert's transformations[9] showing possible development of rhinoceros skull (C) from *Caenopus* (A), through *Gaindatherium* (B).

Huxley[15, 16] and Teissier,[34] in the analysis of growth and the comparison of growth within and between individuals, made extensive use of the power equation, $y = bx^k$, where $y$ was the growth of a part and $x$ the growth of the whole organism ($k$ is the ratio of the specific rates of growth of $x$ and $y$ and may or may not be a constant). Local gradients of growth are readily studied. The chief difficulty is knowing whether $k$ is a constant, or nearly constant, as a result of the ratio of the specific rates being constant, or from their changing in a manner not to affect their ratio; or, if it is not constant, what the variation is and how it is produced.[27, 28] When this simple equation is adequate it should be used. Otherwise, more general methods will avoid confusion that might result from oversimplification.[17, 30] Heterogonic or dysharmonic growth, now referred to as allometric growth, are methods for studying the proportional growth that have contributed both questions and understanding to our knowledge of the shape and form of organisms. Doctor Hersh discusses allometry elsewhere in this monograph.

### *Combining Allometry and Transformation*

Much of my early growth work could not have been done had it not been for the cooperation of Arthur J. Kavanagh. Having published a discussion of the difficulties and limitations in the use of the allometric method,[17, 29] the question was raised as to whether the method could be generalized to include Thompson's coordinate analysis. The main disadvantage of the allometric method is that it compares only two portions of the organism at a time, *e.g.*, length of head with length of body. Although several such comparisons can be made on a given organism, the method, for many, becomes cumbersome. Different numerical values are obtained for different stages and for those regions within a stage not growing at the same rate. The specific growth rates $(dx/xdt)$, $(dy/ydt)$, $(dz/zdt)$ may vary from point to point within part of the organism. While some progress has been made in the matter by subdividing the part and demonstrating gradients and growth activity from one point to another, a more general treatment would be useful.

In the growing organism, the characteristics of growth are continuous and change smoothly from point to point within the organism. In practice, this concept becomes untenable, because, as one approaches regions of very small size, limitations of measurement arise as well as changes in organization from a biological level to a more random, molecular level. The generalized method is limited to the study of the geometrical aspects of growth and of changes in length, area, and volume. Important changes in accretionary growth may occur which are not immediately reflected in changes of size. The details of the generalized method have been published by Richards and Kavanagh,[29, 30] and only the essentials will be summarized here. The fundamental mathematical concepts and basic formulae of the combined method are identical with those that have been developed for the treatment of analogous cases of hydrodynamics and electricity. These concepts are well suited to treatment by vector methods but, since vectorial procedure is less familiar to most students of growth, it is not used.

Suppose tiny bits of material to be imbedded in the growing substance, particles so small that they do not interfere with normal growth, but do not themselves grow. It is convenient to make the original configuration a rectangular network of lines or some other regular system, as Thompson did, but this is by no means necessary. Such experiments have been accomplished by marking rectangular networks on young leaves and by the vital staining of live tissues. As growth proceeds, the configuration formed by these markers changes in shape and size.

The mathematics are designed to reveal the specific rates of these changes. Our method is illustrated by application to Avery's data for the growth of the tobacco leaf.[2] A rectangular network was stamped onto the young leaf and its deformation noted at several stages of growth. FIGURE 7 shows the growth-change analyses. At several points the local growth is indicated by lines, the lengths of which are proportional to the intensity of growth in *length* at that region. Since the direction of maximum growth is at right angles to that of minimum growth, these lines form crosses, as seen in FIGURE 7. Although growth at the midrib is continuous, the nature of the markings did not make it possible for us to use this fact in the analysis. Each half, therefore, was analyzed separately, and the midrib data were used with each half. Slight, apparent discontinuities resulting from this treatment will be seen. Lengths of lines at any one stage are comparable with each other, but are not to be compared with those in the other stages, as the scales are not the same.

The contour marked 100 encloses the region of maximum growth in area at each stage, that of 95 per cent, the region of 5 per cent less than maximum, and similarly to the tip region, growing only one fifth as rapidly in the first stage.

The more general analysis provides the numerical data to obtain the $k$'s of allometry, when they are desired, and with the advantage of information regarding the constancy of $k$. Connecting the several points would give the network and would reveal the transformation from stage to stage due to the growth of the leaf, and mathematical expressions could be derived should they be required. This aspect is the method of Thompson.

For the tobacco leaf, the maximum growth in area remains near the lateral marked 3 for all stages. As the leaf matures, the growth gradient changes from 20 to 100 per cent to 70 to 100 per cent. Similar gradient decreases are to be noted at the sides and base of the leaf. It is incorrect to hold that the ratio of the specific growth rates of two parts remains constant during the growth of the leaf. In the early stage, growth is nonisotropic, but regulation during growth tends toward isotropism and a symmetrical leaf. These geometrical indications point toward active physiological changes that are taking place and correlate with changes in underlying tissues.

This mathematical generalization is available for the analysis of growth in three dimensions, but we have been unable to find adequate measurements of any growing organism. Modern experimental work should include all three dimensions in space as well as in time.

As has already been said, geometrical changes alone may not give a satisfactory picture of underlying growth activity. The change in size at a given

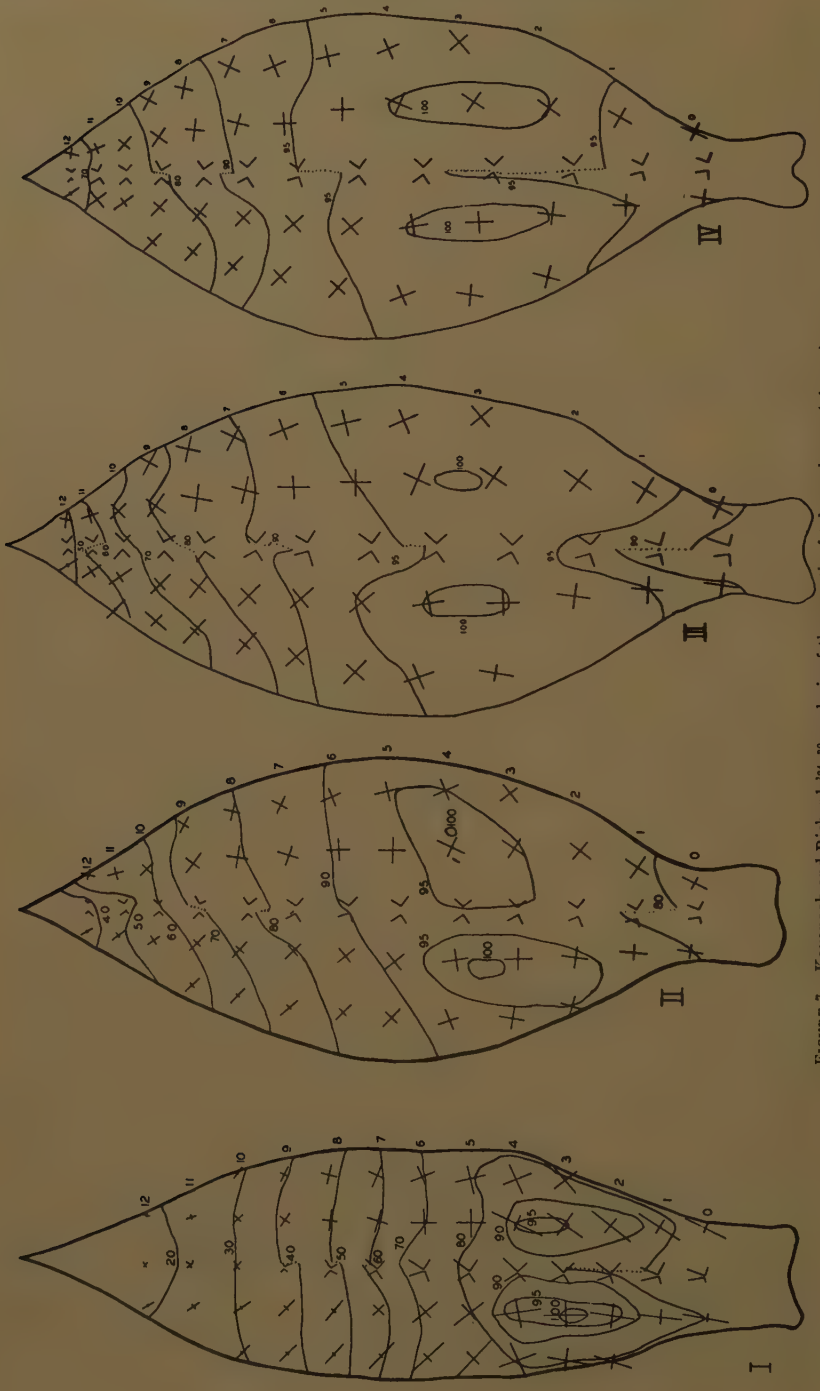

FIGURE 7. Kavanagh and Richards'[24, 30] analysis of the growth of tobacco leaves (*cf.* text).

point is due, presumably, both to the biological activity of the cells located there and to the forces of stretch or compression exerted by the neighboring matter. The more important these forces, the less satisfactory is pure geometical change as an index of biological activity. The shortcomings of geometrical analysis, therefore, call attention to the need for a detailed investigation of the acting forces, and they may thus give a valuable indication of the order of complexity of the processes involved.

The following observations may be made:

(1) If the density (mass per unit volume) is increasing in a certain region, then the percentage growth-rate of mass must exceed that of volume. If, in addition, the volume is increasing or steady, new material is certainly being deposited.

(2) If density is constant, the percentage growth-rate in volume just equals that in size. If volume is increasing, new material is being deposited. If volume is steady, then so is the mass. If volume is decreasing, material is in the process of removal.

(3) If the density is decreasing, the percentage growth-rate in mass must be exceeded by percentage growth-rate of volume. If volume is decreasing, then material is being removed.

Axially symmetrical growth is discussed in the earlier paper, and other geometrical relations of interest derive from the mathematics of the general method, *e.g.*, a condition for *isotropic* growth is that growth in any plane section perpendicular to the axis should be *isogonic.*

### *Shape = Sets of Points*

At about the same time that Kavanagh and I were deriving our general method, Medawar also concluded that Thompson's method should be of greater use in the analysis of growing form than for comparing the adult end results of the growth.[19] Medawar is interested in shape that appears on a graph as a set of points, and generalized transformations should change these as sets by varying the parameters. His method was illustrated by measuring the heights of definite body regions in each stage of the development series for man arranged by Stratz. These values, tabulated by stage for corresponding values (*e.g.*, height at navel) for all the stages, were fitted by polynomial equations. The equations were solved to obtain the best variable parameter for the series. From this, the several positions of the reference locations were computed. The width curves were then sketched in by *ad hoc* correspondence, and the coordinates were located as shown in FIGURE 8.

Medawar thus demonstrates that the shape of *Homo* is a function of age, that the transformation is a typical stretch that is *monotonic* (simply graded) and that the rate of shape change decreases with time (age).

The transformation scheme is an integrity of its own and could be applied to any organism. The parameters are expressed as continuous functions of a continuously variable parameter. Medawar's paper and his discussion in the Thompson Memorial Volume should be consulted for the details and significance of his contribution toward the analysis of growing form.[8]

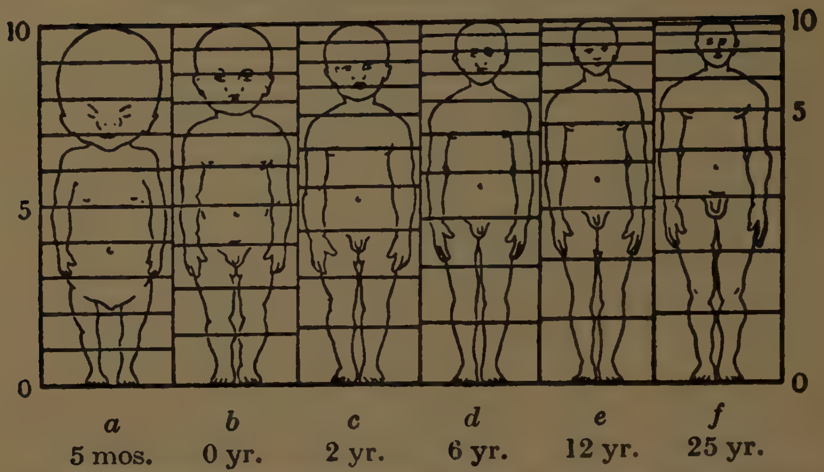

FIGURE 8. Medawar's coordinate transformation method[8] illustrating change of shape in human development

## *Current Applications*

The Thompsonian transformation method has been applied by Lull and Gray[18] to the interrelations of the skulls of the Ceratopsia. These scientists, like Thompson, emphasize that the growing field can be no less than the entire skull. Three lines of development are shown and the deformations that could produce each line are indicated in FIGURE 9. This is an application in paleontology.

Needham has investigated the growth in width of the pea crab (*Pinnotheres pisum* Leach) with respect to the carapace size. Using a modified Medawar method, he obtains a "form cinematogram" for abdomen width.[20] Form, he

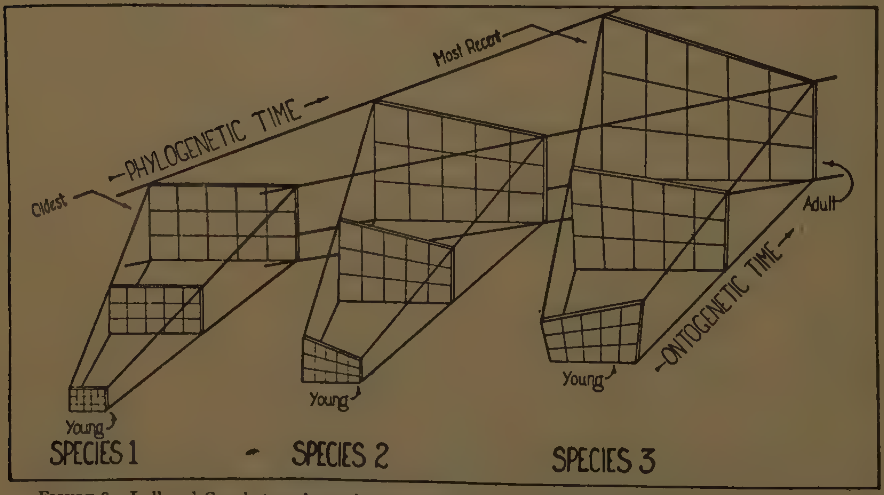

FIGURE 9. Lull and Gray's transformations[18] for three species. Each ontogenetic series culminates in an adult form which falls into line with other adult forms to create the phylogenetic series.

emphasizes, is shape plus size. The over-all changes are shown by reciprocal coordinate transformations from adult to immature female, and from immature female to adult. The alterations from growth are more evident when both transformations can be viewed side by side. The marked growth gradient in segment 4 is seen readily on the graph, less easily in a table of values. The juvenile abdomen (male or female) is essentially triangular and, in the female, develops into a virtually circular shape.

While not a transformation in the strict Thompson sense, Waddington's figures of the developing *Drosophila* wing, with contours showing the regions of more active cell proliferation,[38] can well be considered here, as they are equivalent to the Kavanagh-Richards geometrical indications of the intensity of local growth. These methods promise to correlate geometrical form changes with the internal growth activity producing the changes.

### *Discussion*

The word "growth" means many things to many people. So numerous have its interpretations become that some biologists have proposed abandoning it. Others have started definitions and terminologies. Pending a complete system, the following definition has been found useful and has been adopted in other publications: *Growth* is a fundamental attribute of living organisms, manifested by a change in the size of the individual, or in the number of organisms in a unit of environment.[26]

In discussing methods for analysis, we should consider the nature and use of the measuring scale or scales and how much information is needed for a given problem, but limited time restricts this discussion, and the reader may find general problems considered in other symposia.[22, 33, 46]

Thompson limited his transformations to the shape of closely related adult organisms. He despaired of using them more broadly than to reveal discontinuities in evolutionary series. While geometrical considerations are, of course, more flexible, the actual labor involved in their application could be formidable unless we relegate it to one of the modern electronic calculators. What can the transformation method yield, we may ask, when limited to adult configurations? Would it be possible to obtain a mathematical classification of organisms to complement or supplement that of present taxonomy? Are Spencer's discontinuities real or merely indicative of greater ignorance on our part? Not enough work is yet available to permit us more than a guess at the answers.

Using the transformation method for the analysis of developmental stages, one is usually not troubled by such limitations, although problems and difficulties can be foreseen with the abrupt changes in insect, ascidian, and other complicated development. Yet nature manages these transformations, and we should be able to put them into proper form for mathematical analysis.

Is there a lower limit in size or application to which transformation analysis may be applied? Certainly discontinuous, random molecular activity would not be appropriate for other than a statistical treatment. Yet molecules soon become organized, from stress of one kind or another, into shape or form (as discussed by Bonner,[4] Weiss,[41] and others) which should be analyzable. Cell shapes have geometries which transform into mature organisms.[11] Gradients, fields, and organized patterns are known and, in fact, Medawar[8] has used transformations to show the different tissue culture growth from diffusion gradients in circular and rectangular cells (FIGURE 10).

Woodger[45] comments, " . . . in order to explain taxonomic differences we are not concerned with how one adult could be distorted into another adult shape, but with the problem of how a zygote *a* must differ from a zygote *b* in order that an adult reached from *a* will differ, in a way to be explained, from a time-stretch reached from *b* in an equal interval of time and in a similar environment." A few lines later he says, "We also require a corresponding theory of genetic transformations." This sets an excellent, comprehensive program that should lead to a really general study of growth.

When information can be completely expressed in mathematical nomenclature, it is possible to use mathematical logic to show interrelations, or to lead to conclusions. Even when complete expression is not possible, and the deficiences are known, the use of mathematical methods may be helpful. Will the results be of biological use, or would they simply show that several transformations could be made, each within the errors of the measurements—much as some of us learned, 25 years ago, in fitting serial growth curves? One must admit, however, that the inadequacies of growth-curve fitting did demonstrate the high order of complexity of the process, that autocatalytic and other theories alone are inadequate to explain the principles of growth, and that more critical experimentation is required to provide the considerable information needed for rigorous analyses.

Other approaches should be integrated with these methods: the mathematical studies of Rashevsky;[23] physiological comparisons, *e.g.*, Adolph's charts[1] of functions of organisms; studies of symmetry, Breder,[5] Weyl;[44] of phyllotaxis, F. J. Richards;[25] Brody's[6] and Hammond's[13] comparisons and improvements of food animals; charts and systems of human growth, of Wetzel,[43] Reynolds and Sontag,[24] and others; Sinnot's contributions[32] to shape change with growth; the reconstitution of dissociated sponges and organisms; Weisz' study[42] of

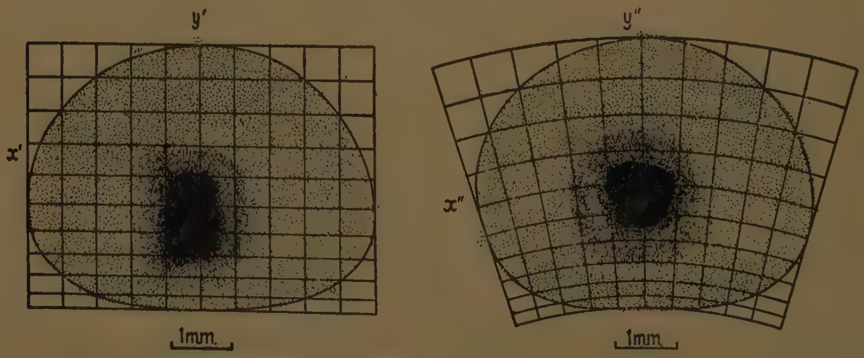

FIGURE 10. Medawar's transformed coordinates[8] of spleen tissue culture distorted by a diffusion gradient from a rectangular cell (left) and a circular cell (right).

segmentation in Artemia; and proposals of Bertalanffy and of Woodger. These are all facets of the biological problem of growth which have bearing on transformation analyses and are necessary to a theory of growth.

More work should be done with some of the human growth measurements. At least, Medawar's method should be extended. Bullen[7] has emphasized human types. The staining experiments and the type stages of embryonic growth[12, 14, 21] are interesting, although they also raise the question of time required to reach each stage and whether each stage represents an additional equal amount of *biological work.* Studies of developing tissues offer promise,[11] likewise Wardlaw's studies[39, 40] on the fern primordium. Some organisms with growth rings or other markings may provide quantitative data. Cacti and some other forms are provided with built-in markers which nearly meet the requirement that the markers do not themselves grow.

General methods are now available to the biologist and could be applied and tested, provided numerical growth information was available. New experiments on growth should be planned in advance to provide the information, as the analytical work may be done more effectively by others than by those conducting the experiment. Still better planning would combine biological, mathematical, and computational skills together throughout the actual growing of the organism and during analysis of the growth data. Some biologists may have facilities for analysis, others for growing living organisms. Thompson's contribution, however, and many other advances in science, suggest that advances are more likely to be individual, although numbers can speed up the availability of measurements and the application of theories.

Since *Homo* is a prime animal for anthropology, the application of transforms could become a useful means for the analysis and the classification of the relation of form and function. It would not be too difficult. Some mathematician interested in biology, or some biologist with a talent in mathematics, should be encouraged to pursue this investigation.

Thompson was concerned primarily with leading the mathematician to the solving of biological problems. Being interested in geometry, he saw immediate and practical need for application in the broad sense of analytical methods, theory of functions, and other higher mathematics. The mathematicians have, indeed, helped us, and at least one generalization awaits numerical information for a test. Other methods discussed in this monograph should provide further advancements. The challenge has been returned to the biologist. Improved experimentation and analysis are in order. May this brief progress report be helpful to physical anthropologists by virtue of its dearth of specific applications and conclusions!

### *Note*

Following the presentation of Doctor Richards' paper at the conference on which this monograph is based, Doctor Herbert Elftman mentioned that conformal representation[47] should also be considered a method of the analysis of growth. The Kavanagh and Richards generalization did include this concept (Clark and Medawar,[8] p. 22).

Two other papers with Thompson transformations[48, 49] are also recommended by Doctor Richards for further reading in this field.

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# AN EXPERIMENTAL STATISTICIAN LOOKS AT ANTHROPOMETRY

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The purpose of this paper is to record some of the reactions that occur when the content and methods of anthropometry are looked at by one who is now an experimental statistician in medicine, but was formerly an anatomist sufficiently concerned with human morphology to become a member of the American Association of Physical Anthropologists. The remarks can be somewhat systematized by examining each of the key words of the title.

## *Modern Anthropometry*

Examining first the terminal word of the title, we consider the modern implications of "anthropometry" as revealed by one of its chief organs, *The American Journal of Physical Anthropology.* During the last five years, I have not been so intimately acquainted with the contents of this journal as I was during the preceding 20 years, but I have recently become immersed in it again, receiving both enlightenment and stimulation, for I find that its field of interest now includes such problems as taste testing, weight lifting, the cholesterol content of the blood, and the variation in urinary excretion patterns studied by chromatography. Doctor Stanley Garn[8] has shown what this expanding interest implies in the education of anthropologists, including training in experimental methods.

## *Statistics*

Another key word in the title of this paper is "statistician." At a summer seminar held in 1951 by the Wenner-Gren Foundation for Anthropological Research, New York, N. Y., a very experienced and mature anthropologist remarked that a certain journal in his field was becoming "too statistical." There was no discussion, even to the extent of asking him which of the definitions of statistics (more than 100 in number[13]) he had in mind, or whether he was merely repelled by the mysterious formulae of mathematically sophisticated writers. If, however, his criticism went deeper than this, and indicated a suspicion that the mathematics masked doubtful assumptions, oversimplified the biology, and disregarded the poor quality of data—then, as an ex-anatomist and as an experimenter, I should often find myself in agreement with him.

But we cannot condemn an art simply because it is misapplied by some of its practitioners. The art that we are considering—experimenters' statistics—began in the first decade of this century, in a brewery chemist's laboratory in Dublin, Ireland, where W. S. Gosset, who published under the pseudonym "Student,"[24] devised a test, later called the $t$ test, for evaluating the means of small samples of measurements. Thereafter, as is well known, the principles and techniques were extensively developed at the Rothamsted Agricultural

Experimental Station at Rothamsted, England, by R. A. Fisher[5, 6] (later Sir Ronald Fisher), and they are continuing to develop in many directions in the hands of many workers. They have spread so widely in applied science that there are very few goods, either grown or manufactured, that have not been influenced at some stage in their production by this form of statistics.

Basically, this variety of statistics expresses the logic of experimentation—the principles of inductive inference. The arithmetic is a subordinate part, but even if the arithmetic is complicated and laborious, it is easier than thoroughly good observation and experimentation, and very much easier than clear thinking. Also, the anwer that emerges from the arithmetic seems like the result of a mathematical proof. Hence the damage done by statistical "cookbooks" that have stressed the arithmetic and neglected the experiment. That introduces another word from the title—"experimental."

### *Experimentation*

In so far as anthropometry becomes experimental, the anthropometrist will wish to use proper methods. To take a very simple problem, the comparison of two treatments of any kind, he will allocate the treatments to the subjects by what Fisher[6] called "a physical experimental process of randomization," such as a table of random numbers. Then, in interpreting his results, he will have only two possibilities to choose between—chance and the treatments—and he can easily find out how often chance, operating alone, would cause the difference that was produced in his experiment.

In seeking advice about experimental methods, however, the anthropometrist should not expect all professional experimenters still in circulation to be acquainted with modern methods, and some may scoff at randomization. Perhaps the best way to appreciate this procedure is to do an experiment or two in which it is properly used, and to note how "unclean" one feels in experiments where it has not been done. (Incidentally, all reports should indicate what the investigator means by "random," because the word is often still used very loosely. Haphazard sampling, or sampling without conscious selection, may be extremely nonrandom.)

The other great contribution of modern statistics to experimental method is the development of designs that not only avoid bias but enable one to obtain a maximum amount of information for a given expenditure of material, time, and money—that is, designs of high efficiency. Some of these designs are rather complicated but very valuable; for example, the recent use of a balanced, partially confounded design in the investigation of the various sources of error in photogrammetry of the human body.[11] In experimenting on human beings, it is usually desirable to keep to simple designs, for it is better to sacrifice some efficiency than to risk jeopardizing the whole experiment by breakdown or loss in a complicated scheme.[18] Randomized blocks, two-level factorials, and switchback designs are usually easy to apply. The switchback or reversal plan is very important where the sequence in which readings are taken may affect their magnitude, as in comparing right- and left-hand force by equipment that is unfamiliar to the subject.

### *Contrast of Surveys and Experiments*

Although an anthropometrist may often experiment, most of the time he must use survey methods, observing what nature offers him, and yet acquaintance with experimental principles is essential for two reasons:

(1) Experimental statistics has had a profound influence on survey methods, as, for example, in the recent Canadian nation-wide survey[22] of statures, weights, and skinfold thicknesses.

(2) If we bear constantly in mind the outline of a simple experiment, we shall be acutely aware of the defects in even the best possible survey. A rather extreme illustration may be useful. An investigator wished to find out whether patients with rheumatoid arthritis differed from healthy persons in the concentration of a certain blood protein. He sent the figures to our department, suggesting a $t$ test for comparison of the two means.

Naturally, we declined to apply any test at all, but we sent him a six-page memorandum telling him why we declined, and suggesting what he might do—briefly as follows:

(1) We recalled the essential difference between his survey and an experiment—no one can randomly allocate rheumatoid arthritis.

(2) We suggested that he prepare a list of factors, other than rheumatoid arthritis, that might conceivably cause a difference in protein levels between his arthritics and his controls (persons at a blood donor clinic). We began the list by mentioning 10 items: sex, age, racial stock, family relationships, diseases or disorders other than rheumatoid arthritis, treatment of patients, diet, physical activity, times and methods of blood collection, methods of chemical and other analysis.

(3) We suggested that he try to show which of these factors could probably be ruled out, either by internal evidence (from the data) or by external evidence (from other investigations).

(4) We pointed out that, after he had done all he could do, there would always remain some factors, either unsuspected or of unknown power, any one of which might cause bigger differences than chance would cause once in a thousand experiments—that, therefore, it would appear rather ludicrous to apply a significance test, as one would after an experiment.

Of course, anthropometrists can usually go much farther in removing bias from surveys than we can in medicine but, in the end, they also are left with the risk of bias from unknown factors, and herein lies the difference from experiments. In all experiments, there are unknown factors, but their effects have been randomly allocated, and, by our test of significance, we can insure ourselves against being "fooled" by these factors more than once in 20 experiments, or once in 100 experiments, whichever risk we choose to run.

### *Statistical Significance*

One may well wonder whether significance tests should ever be applied to survey data, except to convince an investigator that a result that looks impressive could often occur by chance. That is, he would be asked to accept a verdict of nonsignificance ("not proved"), but to disregard a verdict of significance—a rather difficult psychological feat.

Many other things could be said about significance tests,[20] but only one will be mentioned here. To break the tyranny of the $P = 0.05$ standard, some anthropometrists have suggested that, with $P$ between 0.05 and 0.01, the verdict should be "probably significant," but if $P$ is less than 0.01, we should say "almost certainly significant." This may help some people, but it still seems to imply that a significance test can tell us what to think. All that it can do is tell us how often chance, operating alone, causes certain results. The decision then lies with us, and, whatever an investigator may say, or think he believes, the best way to see what level of significance he is adopting is to observe how he acts after he has found his $P$ value.

### *Berkson's Fallacy: Competing Rates*

Returning now to the biases that may lurk in surveys, we note one that is perhaps the most disturbing of all. In our department, we name it after Doctor Joseph Berkson[2] of the Mayo Clinic, Rochester, Minn., who demonstrated that, because hospital admission rates for different diseases differ, entirely erroneous conclusions can be reached regarding the relationship, or lack of relationship, between two diseases. Although this demonstration was published nearly nine years ago, it has only recently started to receive attention in medical statistics. Anthropologists may be better acquainted with it than their writings suggest. If they are not, the best way to start is probably by simplified arithmetic, as in the APPENDIX to this paper.

There appears, at present, no way of preventing or curing this bias, and what we should do in every survey, large or small, is ask: Could there have been present the two conditions, specified in the APPENDIX, that allow this competition between rates to come into play? To answer this question in the study of blood groups or prehistoric remains, we shall have to go back in thought many thousands of years, but we should consider carefully all the possible factors, and we should let our readers know that we have done so.

### *Anthropometry and Medicine*

Berkson's fallacy has brought medicine prominently into the discussion, but the medical point of view obviously has influenced all the foregoing remarks. A short time ago Doctor Krogman[14] summarized the bearing of anthropology on medicine and dentistry and, from the medical side of the fence, as a member of a Study Group on Rheumatic Diseases, I hear, in our weekly discussions, clinicians and laboratory workers telling about their anthropometrical work—methods of assessment, morphological, physiological, and biochemical, in health and disease. It may, therefore, be worth while to consider a few examples of the way in which the three disciplines—anthropometry, medicine, and experimenters' statistics—could help each other.

(*1*) *Clinical normality.* This is a question that theoreticians have argued about for years, but physicians must act every day on some working definition. Here the anthropometrists could help, not only because they know the importance of standard techniques and the risk of errors in measurement, but because they are not so obsessed by disease as we are in medicine. They would be more likely to derive standards of normality from people performing their ordinary functions rather than in a hospital ward or under the so-called "basal" conditions of a metabolism room—a distinction that Doctor Gerda Seidelin[23] has rightly emphasized.

Assessment of normality is a statistical problem, and it is useful to recall the twofold classification of error now commonly used by statisticians in significance testing. Translated into terms of the assessment of a child's weight, a type 1 error occurs when we classify him as "underweight" when in reality his weight, although low in our standard range, is not low from pathological causes. A type 2 error occurs when we accept him as not underweight because it is, say, above the tenth percentile in our standard series, when in reality it is low from pathological causes. This classification of error is not merely convenient shorthand; it focuses our attention on the two risks that we run in all statistical judgments, and it helps us to set our standards. Particularly, it shows the need for knowledge of the range of variation found in each disease—"norms" for diseases.

(*2*) *Differential diagnosis.* The sexing of a skull, like the physician's attempt to decide which of two or more diseases a patient suffers from, raises the question of observation versus measurement—the same question as somatotyping versus anthropometry. The question can be settled only by thorough comparisons of the two methods, and often a combination of both will be found most valuable. When a metrical method involves the combination of measurements of several features on each subject, the appropriate way to evaluate the method is to get the best combination of measurements by discriminant functions. When Fisher[5] first described this technique in the 1938 edition of his *Statistical Methods*, he illustrated it by reference to the sexing of mandibles, but his technique has been curiously neglected in anthropometry until recently.[3]

(*3*) *Psychological problems.* As anthropometrists turn more from bones to living subjects, and from anatomy to physiology, they will meet more problems of psychology, familiar to clinical research workers who try to obtain healthy controls. In our own studies of bone density, for example, it was not difficult to pick up in a few minutes a dozen or more students who were willing to be X-rayed, but several hours spent on personal appeals to business men would sometimes bring in only one or two. It may not be very difficult to induce Australian aboriginals of both sexes and all ages to be photographed in the nude, but to obtain many middle-aged and old citizens of New York for somatotyping would not be so easy. Such a restriction can lead to distorted conceptions, as it has done in biochemical tests for the detection of cancer.[12] Many of these tests have seemed successful at first because controls have been interns, residents, nurses, and young laboratory workers, whereas the cancer patients have been older people, and the tests have been simply detecting age differences.

It must be remembered, also, that those who volunteer as subjects for research are likely to differ from those who do not volunteer—psychologically,[15] therefore presumably also in their physiology, biochemistry, and, not improbably, in their morphology.

(*4*) *Deceptiveness of familiar statistics.* Significance tests are now common in anthropometry and medicine, but in both fields a question that is often of greater importance is: How large or how small may be the true (population) value of this thing that I have tested? That is, what are the confidence limits? These limits often reveal how little we know about the sampled population, whatever the significance test may have shown.[16, 19]

The coefficient of correlation has played a large part in anthropometry during and since the time of Karl Pearson, who contributed so much to biometry in the pre-experimental period. The correlation coefficient is retained in experimental statistics chiefly because of its arithmetical relationship to the linear regression coefficient. Thus, its probability $P$, which can be found from tables,[7] is exactly the same as the $P$ for the corresponding regression coefficient, and this saves the trouble of a special test. Also, the correlation coefficient ($r$) provides (by the use of $1 - r^2$) a quick method of finding the residual variation—the scatter of dots about the regression line. The full implications of correlation are, however, quite inappropriate to experiments, because the values of the independent variate are selected, and the same may be true of surveys. Besides the inappropriate use of $r$, three features are regrettably still common in anthropometric and medical literature:

(a) Standard errors affixed to correlation coefficients, although Fisher[5] pointed out 30 years ago how dangerous this could be.

(b) The use of complex variables, such as ratios and indices, in correlation and regression without previous consideration of what the effects may be—a point to which Gavan[10] has called attention. Sometimes the situation is made even more complicated by the use of the same measurement in forming the X and Y variates.

(c) The use of the correlation coefficient as adequate evidence of the reliability of a technique—to show, for example, how closely two observers agree, or how closely one relatively easy method of measurement agrees with a standard but more difficult method. If the correlation coefficient is used at all, the next step should be to estimate the residual variation. For example, if the coefficient of correlation is +0.995, all except 1 per cent of the total variation between readings by the easier method would be registered also by the standard method, but this 1 per cent, expressed as actual units of measurement, may show that the easier method is by no means precise enough for the purpose in hand. Instead of correlation or regression, however, a familiar simple technique is usually preferable. From the series of differences (reading by standard method *minus* reading by easier method) find the mean difference, *i.e.*, the systematic difference between the two methods, and find the standard deviation of the series, *i.e.*, the variable or random difference between the methods. (When the relationship between the readings by the two methods is curvilinear, special techniques of estimation, of course, have to be employed.)

(5) *The need for further exploration*. The foregoing remarks are not meant to imply that experimenters' statistics can answer all the questions that anthropometrists may ask. It is still a young art, and bears the marks of its origin in biology, where variation between individuals, after elimination of detectable major causes of difference, is often not very far from normal (Gaussian) in form, and where, as sampling experiments have shown, even considerable skewness does not vitiate the $t$ test or analysis of variance. But the techniques are now

being used outside biology. In the work in our own laboratory, for example, we need to know how far they are safe when applied to densitometer readings on X-ray films. We find that our interest is turning very much to techniques that do not assume any form of distribution, Gaussian or other (nonparametric techniques).

Experimenters' statistics retains, also, its interest in averages and in over-all variation, but in assessing clinical normality we are interested in the tails of skew and possibly irregular and truncated distributions. Healthy subjects, as was mentioned above, are not plentiful, and therefore we might think of pooling data from different centers. But even the best laboratories, employing the same methods, differ in their results. Therefore, to pool data might make the range too wide to be of use in any of the centers. Hence our question is: What can be done with "local norms" derived from relatively small samples? Only experiments can tell us.*

In many other directions also, such as factor analysis, exploration is necessary, and this youthful art of experimenters' statistics needs guidance and constructive criticism by those who become informed of what it has done and is trying to do. It could be helped greatly by forward-looking anthropometrists.

## APPENDIX

### *Berkson's Fallacy: Competing Rates*

*The original discovery.* An early demonstration of Berkson's[2] discovery occurred in a search for a possible association between diabetes and cholecystitis. There was such a strong impression of the existence of this association that some surgeons were removing gallbladders in the treatment of diabetes. To test the soundness of this belief, the incidence of cholecystitis in diabetic patients was compared with its incidence in persons who came to the clinic for eye testing, because it could not reasonably be suspected that there was any association between cholecystitis and errors of refraction. The frequency of cholecystitis was found to be higher in the diabetics by an amount that was statistically significant. Then Berkson showed that such results could be entirely fallacious.

*Extension to other surveys.* The fallacy can affect any kind of survey of any material, living or dead, organic or inorganic. In demonstrating it we can use the symbols $A$, $B$, and $X$ to denote any feature, quality, or attribute, and we can retain the hospital term "admission rate." The admission rate for any attribute is the proportion of the possessors of that attribute that appear in a collection. Thus, in many anatomy departments the admission rate for males ($A$'s) is higher than for females ($B$'s). Also, there is often a tendency to admit specially, or to preserve when found, specimens with peculiar features ($X$'s). Substituting a simple arithmetical example for Berkson's general proof, we proceed as follows.

*Simple arithmetic.* Three attributes: $A$, $B$, and $X$. In the population: 1000 persons with $A$, 1000 with $B$. In each of these, 100 persons have $X$ also. Therefore there is no closer association between $B$ and $X$ than there is between *A* and *X*. The admission rates to a certain survey are: for *A*, 50 per cent; for *B*, 20 per cent; for *X*, 40 per cent. To find how many persons with each attribute will come into the survey:

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* In this exploration, the New York University Department of Medical Statistics, New York, N. Y., is fortunate in having financial aid from Eli Lilly and Company, Indianapolis, Ind., and the encouragement of the Company's Counselor on Research Grants, Doctor Donald D. Van Slyke.

Group *A*, *X*. Total persons = 100. Fifty per cent of these, *i.e.*, 50 persons, are admitted because they have attribute *A*, leaving 50 outside. Of these latter, 40 per cent (20 persons) will be admitted because they have attribute *X*. Total admissions = 70. (The same result is obtained if 40 per cent of 100 are admitted first because they have attribute *X*, and then, from the remaining 60, 50 per cent are admitted because they have attribute *A*.)

Group *A*, *not-X*. Total persons = 900, of whom 450 are admitted because they have attribute *A*.

Group *B*, *X*. Total persons = 100, of whom 20 per cent (20 persons) are admitted because they have attribute *B*, leaving 80 outside. Of these latter, 40 per cent (32 persons) are admitted because they have attribute *X*. Total admissions = 52.

Group *B*, *not-X*. Total persons = 900, of whom 180 are admitted because they have attribute *B*.

In summary, the following persons will be found:

| | *X* | *not-X* | *Total* |
|---|---|---|---|
| *A* | 70 | 450 | 520 |
| *B* | 52 | 180 | 232 |
| Total | 122 | 630 | 752 |

The percentage frequencies of *X* are as follows: Of the *A's*, 70 × 100/520 = 13.46 per cent have attribute *X*. Of the *B's*, 52 × 100/232 = 22.41 per cent have attribute *X*.

The difference (8.95 per cent) is very significant, for chance would cause such a difference less than once in 300 experiments. Something more than chance was operating, but it was not the closer association between *X* and *B* than between *X* and *A*. It was the difference in admission rates—a kind of competition between rates. The rate in *A* offers stronger opposition to *X* than does the rate in *B*; *i.e.*, more of the *B's* are left to be admitted because of *X*.

When division is more than dichotomous (*A*, *B*; *X*, *not-X*) the effects are more difficult to visualize, but they must introduce bias in the same way.

Note. Instead of attributes, the symbols can represent measurements, *e.g.*, age in ascending order (*A*, *B*, *C*, *etc.*) and weight (*X*, *Y*, *Z*, *etc.*).

*Necessary conditions.* Using general terms, we can state the two conditions necessary for the occurrence of the bias:

(1) The admission rates of *A* and *B* must be different.

(2) The admission rates of *X* and *not-X* must be different.

*The masking of a real difference.* The bias may mask a real difference, as the reader can demonstrate by doing the arithmetic of the following example. Let all admission rates and the calculation for *A's* remain as in the above example, but let 60 of the *B's* have *X*, instead of 100 (*i.e.*, 6 per cent instead of 10 per cent). (When, in the calculation, 40 per cent of 48 is found to be 19.2, call it 19 persons.) Answer: 14.16 per cent of the *B's* in the survey are *X's*.

*Further information.* Further discussion of this fallacy can be found in articles by Berkson[2] (the original demonstration), Mainland[17] (application to autopsy data), and Mainland and Herrera[21] (application to clinical surveys).*

*Suggestions in the search for Berkson's fallacy.* It is instructive to consider how the bias might arise in various fields, and the five speculations initiated below will serve their purpose if they prompt specialists in each field to replace them by more realistic examples.

(1) Selective admission of unusual specimens into anatomical collections has been mentioned already, but even in departments that preserve the bones of all their cadavers, numerous selection factors have operated before the cadaver arrives—social factors, physique differences, economic status, racial differences (even within the White group). Secular changes occur in the strength of all these factors, including differences in the type of subjects during a severe economic depression. In the investigation of skeletal stature (and the comparison with living subjects' stature) careful thought should be given to the bias due to competing rates.

(2) In the investigation of prehistoric remains, it should be remembered that the preservation of the subjects, and therefore their availability for study, depends partly upon the terrain, and two types, $A$ and $B$, may have lived in different terrains. To qualify as the attribute $X$, this morphological feature would have to be associated with something (perhaps sex, age, or occupation) that tended to promote preservation, whichever terrain its possessors lived in.

(3) The text of the article has referred to psychological differences between those who volunteer as subjects for research and those who do not. We may suppose an association between this and some morphological or physiological feature that is to be investigated ($X$), and if there is also a difference, independent of $X$, in volunteer rate between sexes or racial groups ($A$, $B$) or ages ($A$, $B$, $C$, *etc.*) the stage is set for Berkson's fallacy.

(4) In the examination of soldiers at a separation center for the study of differences in somatotype associated with age, two possibilities would be relevant:

(a) Differences in admission rate to the army associated with age ($A$, $B$, $C$, *etc.*).

(b) Differences in admission rate (or survival rate) associated with physique. Some evidence of association between somatotype and occupation[9] should be recalled in this connection.

(5) In blood group research, if the groups exert selective effects (or are associated with selection factors)[4] or if there is an association between groups and disease,[1] the problem of bias appears to fall into the basic pattern described by Berkson.

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* There has recently appeared an important article by Doctor Berkson (Proc. Mayo Clinic, 1955. **30:** 319) that recounts the history of his discovery before its application to the cholecystitis problem and shows how the bias can produce spurious associations in longitudinal forward-going studies, such as the search for an association between smoking and lung cancer.

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# ALLOMETRY AND ANTHROPOMETRY

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Allometry is a form of differential growth. It deals with the growth of the parts of an organism relative to one another and to the whole organism. Growth is a fundamental property of protoplasm. This raises a host of complex problems that are studied more or less intensively in all the main branches of biology, and one is likely to find that each specialty has its own definition of growth. As used throughout this paper, growth is defined simply as change in size. It is most frequently measured in terms of some linear dimension such as length, width, or diameter, or as change in weight. In the skull, growth is most often measured as the distance between various anatomical points that are distinguished in physical anthropology. The growth involved is usually an increase in size, but also included under the term are the rarer cases of a decrease in size. This is sometimes designated by the term "degrowth," a term which seems repellent to many persons. At any rate, it is not a popular term, and it has not been accepted by any dictionary. An outstanding example of normal decrease in size is that of the thymus gland, which continues to increase in size until it is about two years of age, then remains practically stationary in size until about the 14th year, when it usually undergoes a gradual decrease. The atrophy, in some instances, may also be pathological, as in muscular dystrophy, in which the decrease is principally in the skeletal muscles.

The phenomen of growth has been studied in all ages, from ancient Greece to the present time. At first, however, it was purely descriptive. Quantitative data were originally merely on the height, but the anthropologists now have indices of height-weight, brain weight to body weight, and various indices of the skull. These dimensions were first studied in relation to one another merely as percentages and then, many of them, by the method of statistical correlation.

This study of changing size relations by the method of indices and statistical correlation has been superseded for many data by the allometric method, although the other methods are still valuable for some purposes.

Allometry is the form of differential growth in which the data conform to the power function

$$y = bx^k$$

which in logarithmic straight line form becomes

$$\log y = \log b + k \log x$$

In this equation, $y$ and $x$ are the growing parts, and $b$ and $k$ are constants. The equation was first used by Snell in 1891. It was given a great impetus in 1924 by Huxley, who summed up the results and discussed the problems it involved in his book *The Problems of Relative Growth* (1932) and, more recently, in a chapter in his *Essays on Growth and Form* (1945). The first use of the equation was on the brain weight/body weight relation. This particular problem has been taken up more recently by Count in his monograph *Brain Weight and Body Weight in Man* (1947), in which he discusses brain weight/body weight antecedents in growth and evolution. The problem is brought up to date in this monograph by Doctor von Bonin.

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* While this article was in press, The New York Academy of Sciences received news of the death of Doctor Hersh in Cleveland, Ohio, on August 28, 1955.

In the equation, the constant $k$ usually is called the growth constant or growth ratio, and can be given a general biological meaning. On the graph, $k$ is the slope of the line; $b$, the value of $y$ when $x = 1$, is termed the initial growth index. It is the $y$-intercept. It can be given no general biological meaning, but it can sometimes be given a special meaning, having regard to the particular case. It happens that the value of $b$ depends upon the unit of measurement used, while the value of $k$ does not. Before discussing the results obtained by the use of this equation, it may be well to point out certain criticisms in its use. First, the equation is only a rough empirical approximation. Actually, the data points in most cases, when plotted on a logarithmic grid, form a more or less narrow band, whose edges are roughly parallel, and the exact line going through the band is perhaps a curve and not a straight line, at least in many cases. Another criticism of the equation grows out of the fact that there are five different methods for the determination of the constants, and these do not all give exactly the same values. Without going into the details of these methods, they may be briefly mentioned. The simplest method is to fit a line by inspection to the data points, and determine the value of $k$, *i.e.*, the slope of the line. A second method is to derive two simultaneous equations from the data and solve for the two unknowns $b$ and $k$. This is sometimes called the method of averages. A third method is that of the well-known least squares, so widely used in the physical sciences. This method implies that there is variability in only one of the variates. Kavanagh and Richards (1942) pointed this out, and developed their method of least quadratics, which does take into account the variability of both $y$ and $x$. Theirs is the fourth method. The fifth method was developed recently by Haldane in 1950 (see Zuckerman, 1950). It is based on a rather simple relation between the coefficients of variation of $y$ and $x$, and Haldane regards his method as more accurate than any of the other methods. It has been determined for at least one set of data that this method gives higher values of $k$ than the regression methods (Reeve, 1950; see Zuckerman 1950). The differences in the constants derived by these methods (in so far as they have been compared) are usually small and lead to the same general conclusions. By whatever method the constants are estimated, the values of $k$ usually fall between 0.50 or a little higher, when the variates $y$ and $x$ are from the same growth cycle. In those cases where the change in $x$ is a decrease, then $k$ has a negative value. But the values of $k$ do not occur at random. The most common values below one are 0.73, 0.82, 0.88, and 0.95. The most common values above one are the reciprocals of these, namely, 1.37, 1.22, 1.14, and 1.05. Most of this reciprocal relationship no doubt arises from the fact that it is somewhat arbitrary which of the variates is taken as $x$ and which as $y$ in the allometric relation. This reciprocal relationship in the value of $k$, however, is sometimes in the material, and is in no sense an artifact of the kind mentioned. From extensive data on a macaque monkey (*Macaca mulatta*), Lumer and Schultz (1941) showed that the value of *k* for the thigh length/trunk length relation during prenatal growth is 1.14. During postnatal growth, the value of *k* for the same relation is 0.89, which is very approximately the reciprocal of the prenatal value.

There are other similar changes in the value of *k* that inhere in the data, but little or nothing is known of their significance or of the physiological mechanism by which they are attained. The values of *k* that fall between 0.5 and 1.50 are for the elements $x$ and $y$ in the growth pattern which fall in the same growth cycle. In the grand period of growth of the organism, however, there are epochs, and perhaps these have been most adequately discussed by Teissier (1937). These cycles of growth are usually overlapping and do not fall into a distinct sequence. They may, however, be separated in time, as the circumnatal and the adolescent cycle in man.

If $x$ and $y$ are elements from different cycles, but overlapping periods of growth, then *k* can have exceptionally high values. An outstanding example to illustrate the point is furnished by the extensive data on the growth pattern in the house wren (Huggins, 1940). After hatching, the house wren has a nestling period of 15 days before it reaches full growth, when it leaves the nest. Mrs. Huggins found that by the eighth day the body length has reached nearly 90 per cent of its final value, but it is just at this time that the cycle of growth for the feathers is getting under way. The result is that the value of *k* for the feathers that were measured is very high—about 18—and the value of the constant *b* is exceptionally low.

There are no satisfactory human data, so far as I know, to give a concrete example of this point. But consider the possible case of the length of the beard to the total height when the beard begins to grow. At that time, the young man is well along in his adolescent growth toward final stature. If, at that time, the beard were measured and allowed to grow to its full length, then it is almost certain that the value of *k* for the length of the beard/total height relation would be rather high. Let us take an extreme case. Suppose a fully grown man were to let his finger nails grow and, day after day, were to measure the length until their final length of about two inches was reached. Then, if the data were plotted logarithmically, there would be but one point on the $x$ axis, and the line for the data points would be perpendicular to it. The value of *k* would be infinite, since it is the tangent of the angle that the line makes with the $x$-axis.

The time course of increase in size of the organism and its parts is universally sigmoid, although, to be sure, there is a difference in time during the life history when the various parts begin their growth and reach their final size. Of the mathematical equations that have been used, the two most common are the symmetrical sigmoid curve, with the point of inflection at one half of the asymptotic value, and the Gompertz curve, with the point of inflection near the one fourth value, strictly the $1/e$ value where $e = 2.718$, the base of the natural logarithms. Then it is possible, simply as a mathematical problem, to derive the relation between the mathematical equation describing the sigmoid course of $y$ to that describing the time course of $x$. Lumer (1937) had done this for both the generalized autocatalytic and the Gompertz curves. The result is an equation that, when values are plotted, gives complicated curves differing from allometry, except in very special cases. Segments of the curves (see Lumer, 1937), however, might be regarded as conforming to the allometric equation. The general result again emphasizes that the allometric equation is an empirical approximation that is not based on any mathematical law of growth.

In the literature, the equation has been applied to a wide variety of data. The data are by no means homogeneous (Hersh, 1941; see especially Kavanagh and Richards, 1942); $x$ and $y$ may refer to parts of the same individuals as they increase in size, or $x$ and $y$ may refer to average measurements taken at comparable ages on a series of individuals. Again, $x$ and $y$ may indicate measurements taken from individuals grouped into size classes or, again, $x$ and $y$ may refer to homologous dimensions on a series of adults of the same genetic type that differ in size, or of adults of different size that belong to different species. Huxley has called these last two cases adult size allometry or allomorphosis and, in these cases, the results have an evolutionary significance, in contrast to the others in which the results have an ontogenetic significance.

The most desirable data for studies of differential growth are the measurements of $x$ and $y$ made on a series of the same individuals during their main period of growth. Such anthropometric data are not available, and are very scarce even for experimental organisms. But when such data are available, then $k$ is the ratio of the specific growth of $y$ to that of $x$. The more usual type of data consists of measurements of $x$ and $y$ taken on a group of individuals arranged according to age classes, or merely different size groups. Sets of anthropometric data of this kind are still rather few but, when available, $k$ could still be regarded as an approximation to the ratio of the specific growth rates of $y$ to $x$. Usually the data represent a more restricted range from a segment of the period of growth on groups classified merely on the basis of size differences. It is clear that in such cases $k$ can merely represent the ratio of the percentage increase in $y$ to that of $x$. So far, the discussion has dealt mainly with the allometric equation and the meaning of the constants, in an attempt to show something of the limitations as well as the advantages of the method (for further comment and discussion see Reeve and Huxley, 1945; Richards, 1945; Sholl, 1945). It hardly need be mentioned that the relationships involved have been worked up on nonhuman material.

The main purpose of this paper is to relate the allometric function to human data. The result, I greatly fear, will be somewhat disappointing. Naturalists and anthropologists have been taking measurements on man for several centuries. One of the earliest of these investigators was the French naturalist of the 19th century, Buffon, who actually took the height periodically of the same individual from infancy to final adult stature (Sholl, 1954, figure 3). It seems remarkable that after nearly 200 years Buffon's subject is the only person whose growth in height has been followed through from infancy to adult stature. During this interval there have been many measurements made, especially on the various skull indices, in an attempt to distinguish types, races, and various anthropological subgroups. This attempt, in the main, has recently been given up in favor of blood group determinations that rest upon a known genetic basis, which was never the case with the various indices of the skull, and one gets the impression that more headway is being made by use of the blood groups. The various indices of the skull and of other parts of the body are of little use in the study of allometric growth.

It may also be of interest that the term "anthropometry" was used by Bertillon in 1883 for a system of personal identification based on a certain number of measurements of the skeleton. The system was soon widely adapted to police methods for the administration of justice. This method was later given up after the superior system of finger prints was recommended, a system in which Bertillon was also one of the prime movers.

After the few precursors, the work on allometric growth did not get under way until 1924, when Huxley published a note on the subject. The considerable amount of work that accumulated was summarized, and the problems involved were discussed by Huxley in his book published in 1932. In this work, Huxley briefly mentions the work on human fetal growth and comes to the tentative conclusion that Scammon's extensive data would be much better fitted by the allometric equation than by the linear formula that Scammon himself used.

Since 1932, very little has appeared that deals with anthropometric data from the allometric point of view. The data, however, continue to accumulate. A recent extensive series (see Sholl *et al.*, 1949) from England shows that $x$, taken as total height, and $y$, taken as leg length, forearm length, and jaw length conform to straight lines on an arithmetic grid, and so allometry is not involved. The result shows a postero-anterior gradient that generally follows the antero-posterior gradient of prenatal growth (see Medawar, 1945).

The skull is the most interesting element in the growth pattern and also the most complicated to study from an allometric point of view. Brodie (1941), on the basis of measurements taken from X-ray pictures on 21 different children ranging from three months to eight years of age, has concluded that the pattern of growth of the human skull is established at a very early age and then does not change. This seems to be typical of mammalian growth. Brodie did not publish the data on which his study was based, but they were made available to Count (1942) who analyzed them from the standpoint of the allometric equation. The measurements were on the brain case, the nasal area, and the upper alveolar area, including the maxillary teeth and the mandible. Count showed that the growth in time is logarithmic and that only in exceptional cases would one ever expect to find a rectilinear ratio between any two dimensions, $x$ and $y$, but that at the same time there are deviations from the allometric relation. Broadbent (1931), whose main interest is orthodontia, recognized many years ago that to secure accurate and useful information in the normal development and growth of the teeth, jaws, and face, it was necessary to develop a new and more reliable technique. He initiated experiments that led to his invention of the Bolton cephalometer for taking X rays of the head and face and for recording precisely the progress of growth of the teeth and jaws in relation to the cranial base. He has studied a series of the same individuals from one month to adulthood. He has been able to establish that at the completion of the deciduous dentition there is no marked change in the proportion of the face. The horizontal palate and the inferior border of the mandible descend, maintaining the same angle to the cranial plane as it was at three and one-half years (Broadbent, 1941). Broadbent's long continued research is a model of its kind and, in the opinion of the writer, is the kind of work which should be extended to the entire skeleton. But the planning for such an extensive research over a long period of time requires more courage and resources than most individuals can muster. It is obviously a research program that requires the organization and continuous labors of an institute. As so often happens to extensive research of this type, extensive series of measurements made by Broadbent have never been published. The main results, from the standpoint of relative growth, are now in preparation, and may soon be published.

After growth constants, indices, and the like have been quantitatively determined, the problem naturally reduces to one relating to the growth processes that bring about the mature growth pattern. This problem is obviously to be solved only on the basis of some suitable experimental procedure. Consequently, about the best one can do in anthropometry is to obtain experimental results on other mammalian forms and make the assumption that the main general results likewise apply to man.

By the use of the vital staining technique, growth studies have been made on the pig, the monkey, and the rat. The main general results have been extensively described recently by Baer (1954). By this method Baer has studied the growth of the individual bones in the rat, using about 77 specimens over the entire growth period. Baer finds that the individual bone is the unit of growth, but there is little conformation to the relative growth equation. Contrary to the speculations of physical anthropologists on the basis of merely descriptive data, Baer finds from his experimental data that there are two basic systems of growth in the skull. One of these involves the expansion of the brain case, which is related to the rapid growth of the brain. The second, slower growth is of longer duration and results in the growth of the cranial base and, consequently, involves the growth of the face.

Concerning the phylogenetic growth in man, everyone knows, in general, the difference, let us say, between the apes and man. Here again, however, there are for the most part merely descriptive data, and the same is true of the human fossil data. Whatever quantitative data there are are far from sufficient to treat from the standpoint of allometry. The quantitative data available concern mainly the increase in brain capacity with the resulting effect on the brain case of the skull. This is a topic fully discussed elsewhere in this monograph by von Bonin, but the data are very inadequate. As von Bonin says, "Racial differences are extremely vague." In other words, the quantitative data on the phylogenetic growth in man are even more meager than on the ontogenetic growth pattern. The pertinent data involve, principally, the increase in brain capacity with the resulting effect on the brain case of the skull, from Java man through Cro-Magnon man to modern types. The data have not been shown to conform to the allometric equation. The fossil data on the human skeleton are also too meager and fragmentary for any allometric tests.

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## *Discussion of the Paper*

DOCTOR OSCAR W. RICHARDS (*American Optical Company, Southbridge, Mass.*): Sigmoid growth is not inconsistent with allometric growth, as shown by Lumer for some cases, and generally by Kavanagh and Richards. Which methods should be used for fitting the equation should be determined by the nature of the growth measurements and analytical program. Criteria and methods for this are published. The values of $k$ are not restricted to the small groupings stated by Doctor Hersh. I have published a case where $k$ passed through negative infinity! For many studies, it is preferable to compute the specific growth rates and to determine whether and how $k$ varies during the growth period. When the exponent $k$ of the power equation is not constant, examination of the variation may be of more value than using the allometric equation. The Stratz figures shown by Hersh to illustrate complex patterns actually have been analyzed by Medawar and show a simple, monotonic decrease in linear growth.

# ROLE OF ANTHROPOMETRY IN THE STUDY OF BODY COMPOSITION: TOWARD A SYNTHESIS OF METHODS*

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## INTRODUCTION

"It seems evident that the morphologist, the biochemist and the biophysicist should all be concerned with the progress of one another in their respective fields and whenever possible, correlation of morphological, biochemical and biophysical information be made. Much knowledge has accumulated from each of these three fields of study but on the whole such knowledge is in the descriptive stage and awaits integration for insight into one aspect of the anatomy of life" (Wolbach, 1953, p. 254).

The author of the above "motto" was speaking about experimental scurvy and the role of the deficit of ascorbic acid in its etiology; but he might have referred, almost as well, to the study of body composition. This, too, is a complex problem the study of which requires the pooling of skills developed in a variety of disciplines. The physical anthropologist has a legitimate interest in this field and can make specific and important contributions to its development.

In the past, physical anthropology—whether utilizing somatic measurements or ratings, living subjects, or pictures—tended to be concerned excessively with body form, largely neglecting or only obliquely and vaguely considering the "substance" of the body. In this way it has failed to contribute in full-measure to the study of metabolism, physiological functions within the limits of clinical normality, and the tendency toward the development of disease, particularly the noninfectious, noncongenital, degenerative diseases in which heart disease plays such a distressingly large role.

In the past 15 years, important new tools were developed for a quantitative assessment of the principal tissue masses, based on biophysical (body density) and biochemical methods (body water and its fractions). The "soft-tissue" roentgenograms provide means for the measurement of the depth of the subcutaneous adipose tissue (plus skin) and, in the limbs, for the quantitative separation of the muscle and bone segments. Because of the simplicity of the procedures and favorable considerations of time expenditure and financial investment, estimates of body composition in a variety of situations will rely on the direct anthropometric techniques.

Thus there are practical, as well as theoretical, reasons for considering external body measurements, including skinfolds, in reference to the data provided by X-ray analysis, determinations of body density and measurements of body water, in a larger framework of experimental and descriptive human biology. One of the pressing problems is to develop an adequate system of

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measurements for the characterization of body composition on the basis of somatometric data and to provide equations for their "translation" into the more complex and more comprehensive systems.

Because of the important practical implications, as in the field of nutritional anthropometry (Brožek, 1953), concern with matters of body composition should provide a potent stimulus to research in the physical anthropology of the living man. More than that, it may serve to clarify (I am tempted to say, "revolutionize") much of our thinking.

However, it is a fact that the principal impulse for the anthropologist's concern with the "third dimension" of body build, with weights and volumes of tissue masses, has come from the pressure for action rather than from pure meditation, from the rude world of applied science rather than the gentle realm of theory. Matiegka, the Czech anthropologist who first proposed in 1921 a system for the partitioning of the human body in terms of gross morphological components (muscles, skeleton, and adipose tissue), published his provocative paper under the title of "The testing of physical efficiency" (*cf.* Škerlj and Brožek, 1952). Perhaps it was this functional—dynamic, if you wish—approach, foreign to the anthropologist of his day, that helped to bury the paper and keep it in an almost complete oblivion for decades. The roentgenographic soft-tissue analysis was introduced in this country by pediatricians (Stuart, Hill, and Shaw, 1940). Our own concern with these problems stemmed from the need for more satisfactory criteria of certain aspects of nutritional status, of "nutriture" (Keys *et al.*, 1950).

In spite of this "applied" orientation and motivation of anthropological research on body composition, the concepts and the data are of *fundamental* importance for what Matiegka called "somatic" anthropology, the anthropology of the living (and that means changing) man.

Theoretically, interest in body composition is closely tied with the study of human variability, including both group and individual differences (Keys, 1949). In reference to this point it should be noted that the amount of fat is one of the most variable body components. For this reason alone it is understandable that studies on body composition placed a heavy emphasis on the evaluation of this component.

Garn's data may usefully illustrate the relative variability of several anthropometric variables. In a group of adult men (mean age 41 years, range 20 to 69) the coefficients of variation were 2.8 for height, 11.9 for weight, while the respective values for the thickness of subcutaneous fat layer, measured at 9 sites on the basis of soft-tissue teleroentgenograms, had a range from 25.3 to 43.9 (Garn, 1954). The fact that skinfolds tend to show more highly skewed distributions than the other body measurements, with few high values resulting in large (and not strictly valid) standard deviations, accounts only in part for the very large differences in the coefficients of variation noted above.

## METHODS

A variety of methods is available for the assessment of body composition. They vary widely in precision, in the complexity of manipulations and of theoretical assumptions, and in applicability.

TABLE 1

BASIC CONCEPTS OF BODY COMPONENTS

| Anatomical | Chemical (Direct analysis of cadavers) | Histochemical (Indirect analysis *in vivo*, estimates of chemically defined "tissue" masses) |
|---|---|---|
| Adipose tissue | Fat (ether extract) | Fat estimate (equivalent of ether extract) |
| | Total body water (by desiccation) | Total body water and its fractions (by dilution) |
| Muscle mass<br>Viscera | Protein (6.25 × nitrogen) | Cell mass (estimate) |
| Skeletal mass | Total and bone mineral (ash) | Bone mineral (estimate) |

The problem will be approached differently, in terms of *basic concepts*, not merely procedures, depending on one's technical training and aims. The anatomist, working with mechanically separable tissues, the organic chemist analyzing a whole cadaver, and the biochemist and physiologist dealing with a living organism will operate with different basic body components. We have to be aware of these differences before we can attempt any synthesis. The anatomist thinks in terms of dissected tissues and organs that can be measured in size and weighed. The organic chemist speaks in terms of petroleum ether extract, total nitrogen, and ash. The "histochemical" approach and breakdown of body weight into chemically defined tissue (*histos*) masses is guided by metabolic and physiological considerations. The basic concepts used in the different approaches to body composition are indicated in TABLE 1.

The physical anthropologist (whether he is making anthroposcopic ratings, using direct body measurements or measuring the width of tissues in a roentgenogram) is closer to the anatomist than to the chemist. His "fat" is the adipose tissue and his measurements of "muscle" and "bone" refer to anatomical entities. His body components are, then, those of the anatomist. However, unlike the anatomist, he cannot put the man together, so to speak, after he has taken him apart. There are no sky hooks, no bootstraps by which the anthropolgist can lift himself and proceed, unaided, from the measurements

TABLE 2

BASIC DATA IN DIFFERENT APPROACHES TO BODY COMPOSITION IN VIVO

| "Surface" anthropometry | Roentgenogrammetry | Densitometry | Hydrometry |
|---|---|---|---|
| Height, weight, relative weight (actual, as per cent of standard) | Body weight | Body weight | Body weight |
| Skinfolds | Width of skin plus subcutaneous tissues | Body density (D = mass/volume) | Total body water |
| Circumferences and diameters (especially in limbs, preferably corrected for subcutaneous fat) | Width of muscle layer (in limbs) | Extracellular fluid | Extracellular fluid |
| Bony diameters | Bony widths (degree of bone mineralization) | | |

of the isolated segments of the body to a valid estimation of the masses making up the body as a whole. By himself, he is largely limited to *relative* assessment of the individual's adipose, muscular, and bony development.

It is only by correlating his data with the body components determined and defined by anatomical procedures or the densitometric and hydrometric analysis that he can arrive at estimated amounts of total tissue masses. The basic data involved in the different methods for the characterization of body composition studied *in vivo* are summarized in TABLE 2.

Here we shall limit our considerations to the general features of the methods, omitting the details of procedure. The quantitative assumptions of the densitometric and hydrometric methods were presented elsewhere (Keys and Brožek, 1953; Brožek, 1954; Behnke, 1954).

## PROBLEMS AND GOALS OF A SYNTHESIS

No attempt will be made to examine in an exhaustive manner the complex questions pertaining to the synthesis of the available methods for the study of body composition. Elsewhere it was pointed out that the estimation of total body fat ($F$, as a fraction of body weight) from equations involving only body density ($D$), such as

$$F = 4.201/D - 3.813$$

(Keys and Brožek, 1953, p. 280), assumes a normal hydration of the body. Where such an assumption is not valid, information on the amount of extracellular fluid ($E$, expressed again as a fraction of body weight) makes it possible to correct for deviations in hydration, provided the intracellular hydration remains constant.

The formula, with a correction for variations in hydration, is as follows:

$$F = 4.149/D - 0.283E - 3.717$$

This exemplifies the synthesis of two methods, a biophysical and a biochemical method, in the interest of increased validity. In this presentation we shall be principally concerned with the problems of synthesis in special reference to their implications for anthropometric evaluation of body composition.

A simultaneous application of two or more methods yields data necessary for developing an internally consistent system and for the prediction of body composition on the basis of somatic measurements, enables the investigator to present a more comprehensive description of man's physique, clarifies the validity and the limitations of the procedures, stimulates the development of additional methods, and facilitates a correct interpretation of the physiological significance of the individual differences in body composition. Due to the limitations of space, references will be limited largely to the work reported from the Laboratory of Physiological Hygiene of the University of Minnesota.

### (*a*) *Consistency*

The problem of achieving internal consistency in reference to the densitometric and the hydrometric method was discussed elsewhere (Brožek, 1954, pp. 266, 278). It involves both concepts and numerical relations. On the conceptual level, the need is apparent for using tissue masses that are identical, such as chemically defined fat and bone mineral, or "translatable" (cell solids + total body water = cells + extracellular fluid). Mathematically, the internal consistency in the Minnesota system (Keys and Brožek, 1953) was achieved by slight adjustments in some of the biological "constants" in the estimation equations, within the range of plausible variation. Present uncertainties in the conversion factors may be reduced only by a critical analysis of data provided by a simultaneous application of the hydrometric and densitometric method. Some differences between the "model" of a system and a particular set of empirical data, depending on the validity and precision of the particular methods used and the nature of the subject sample, must be expected.

The internal consistency of the more complex methods is of interest in this context principally in so far as it affects the prediction of body composition from anthropometric measurements. Clearly, a common frame of reference will make it possible to combine experience obtained in correlating somatometric data with the results of biophysical and of biochemical methods, thus increasing the possibilities of "translating" the direct and X-ray body measurements into the more comprehensive systems of analysis.

Because of the effects of compression, which may exhibit sex and age differences, additional data are needed on the measurements of skinfolds made in the same subjects by calipers and from roentgenograms, using the same site. Valuable information will result from the consideration of the two anthropometric approaches also in reference to the muscular and bony development, evaluated on the basis of limb measurements.

### (*b*) *Prediction of Total Fat*

In the living man, the percentage of the body weight represented by fat is the best single criterion of the individual's over-all leanness-fatness. This value, as indicated above, may be estimated either from body density or from measurements of total water and extracellular fluid. Both techniques yield an estimate of the *total* body fat while the direct skinfold measurements or soft-tissue X rays provide information only on the subcutaneous fat but not on the deeper internal fat depots. Furthermore, the presence of individual differences in the relative width of the layer of adipose tissue at a given sight complicates the sampling of the thickness of subcutaneous fat. The investigator is faced with the *selection* of skinfold sites which yield the maximum of information and with a problem of the most effective *weighting* of individual skinfolds in order to arrive at the best estimate of leanness-fatness.

Equations were developed (Brožek and Keys, 1951) for estimating specific gravity (and the corresponding percentage of body fat, using the formula proposed by Behnke and his collaborators, Rathbun and Pace, 1945) from five skinfolds and relative body weight. The coefficients of multiple correlation were 0.876 for a group of young men (mean age 20.3 years, $S. D. = 1.9$ years, $N = 133$) and 0.744 for a group of middle-aged men (mean age 49.0 years, $S. D. = 2.8$ years, $N = 122$). Following the method described by Johnson

(1949, p. 339), variables not contributing significantly to the accuracy of prediction were eliminated in order to reduce the labor involved in making the measurements and calculations. By using only three skinfolds (abdomen, chest, and arm), the multiple $R$ for the young men was reduced only slightly ($R = 0.871$, standard error of estimate = 0.0062 body density units).

Interestingly enough, in both age groups the skinfold measured at the back of the upper arm had the largest weight in the prediction equation. In the older group, the constellation of the best predictors was somewhat different including, in addition to the arm and chest, the subscapular skinfold and relative body weight also. This difference, if confirmed in other samples differing in age, will complicate the problem of translating the somatometric data into the densitometric system. There are other factors that must be considered, including the relative rates of accumulation of fat in the external and internal fat depots. This matter will be discussed later.

The prediction equations were developed with specific gravity as the criterion. In the interest of uniformity and simplicity, the equations were recalculated (Brožek, 1954, p. 276) in terms of body density, $D_B$ ($D_B$ = Sp. gr. × $D$ of water in the tank in which the subjects are weighed under water). Two other facts concerning these data should be noted: (1) an average correction rather than individually determined values of residual air was used, and (2) the skinfolds were measurd by calipers with a very small contact surface and a high pressure (about 35 gm./mm.$^2$) which rose somewhat when the opening of the calipers was increased in order to measure a larger skinfold.

The problem was restudied at the Army Medical Nutrition Laboratory, Denver, Colo., with calipers yielding a standard pressure of 10 gm. per square millimeter of the contact surface (Pascale, Grossman, and Sloane, 1955). In 88 healthy young soldiers (mean age 22.1 years) skinfold measurements were made at 11 sites. Using only those skinfolds that contributed significantly to the prediction efficiency, the following prediction equation was derived:

$$\begin{aligned}\hat{D} = 1.08012 &- 0.0007123\,S\\ &- 0.0004834\,C\\ &- 0.0005513\,A\end{aligned}$$

where $\hat{D}$ = the predicted body density; $S$ = skinfold thickness in mm., measured at the "side" (on the chest in the midaxillary line at the level of the xyphoid process); $C$ = "chest" (in the juxta-nipple position); and $A$ = "arm" (on the dorsum of the arm at the midpoint between the tip of the acromion and the tip of the olecranon). The coefficient of multiple correlation for this equation was $R = 0.85$ and the standard error of estimate was 0.0065 body density units. The $R$ does not exceed, as could have been expected and hoped for, the value obtained for the young men studied at Minnesota. The mean body densities and the standard deviation in the two samples were similar (Minnesota, $\bar{D} = 1.0701$, $S.D. = 0.0140$; Denver $\bar{D} = 1.0678$, $S.D. = 0.0120$), the Minnesota density values being slightly higher, on the average, and exhibiting somewhat higher scatter. The Minnesota subjects were almost two years younger.

The prediction of body density from skinfolds was studied in the Laboratory of Physiological Hygiene also in a sample of older men, for whom the amount of air remaining in the lungs and respiratory passages at the time of underwater weighing was determined directly, a group of women between 20 and 60 years of age, and a small group of men serving in a study on experimentally induced obesity. The results of these observations will be reported elsewhere.

### (*c*) *Comprehensive Description*

In the preceding section, emphasis was placed on the estimation of the total body fat from skinfold measurements. However, the fact should not be overlooked that there are substantial interindividual differences not only in the absolute but also in the relative thickness of subcutaneous fat at different sites. From the point of view of predicting total body fat, this fact is largely a nuisance, requiring us to sample the thickness of the subcutaneous fat at more than one site if we wish to reduce the effects of individual differences in the pattern of the distribution of superficial fat.

From the viewpoint of a comprehensive description of human physique, these differences are of interest in their own right. While in measuring the body density we integrate the fat depots, skinfold measurements and soft-tissue X rays allow a numerical portrayal of the *distribution* pattern. The problem of fat patterning as an individual characteristic was examined by Garn (1955). By relating the departure of an individual value for each site ($X_i$) from the group mean ($\bar{X}$) to the standard deviation [$z = (X_i - \bar{X})/S.D.$)], one arrives at a relative fat pattern.

In the course of a weight loss associated with maintenance on survival rations, the relative fat pattern remained fairly stable. The study was carried out at the Laboratory of Physiological Hygiene in cooperation with Doctor Garn. As an example, in FIGURE 1 the profiles are given for a subject studied during the control period and, after 24 days of caloric restriction, resulting in the total loss of about 11 per cent of body weight. The top line refers to the control

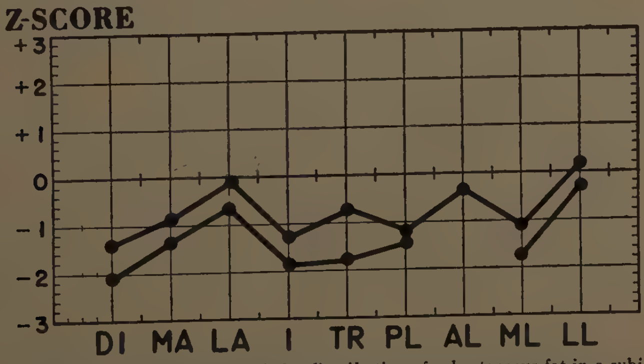

FIGURE 1. Relative pattern of the distribution of subcutaneous fat in a subject studied before and after experimentally induced weight loss (see Garn, 1955, p. 83). The letters refer to the following sites: deltoid insertion, medial arm, lateral arm, iliac, trochanteric, posterior leg, anterior leg, medial leg, and lateral leg.

TABLE 3

SKINFOLDS, BODY DENSITY AND BODY FAT IN NORMAL YOUNG AND MIDDLE-AGED MEN

| | Young men | Middle-aged men |
|---|---|---|
| N | 133 | 122 |
| Age, years | 20.3 | 49.0 |
| Relative body weight | 101.4 | 101.8 |
| Skinfolds, mm. | | |
| Abdomen | 18.2 | 25.5 |
| Chest | 15.9 | 24.5 |
| Arm | 10.9 | 14.4 |
| Actual density | 1.0700 | 1.0489 |
| Calculated body fat, per cent | 11.3 | 19.2 |
| Estimated density (from skinfolds) | | 1.0574 |
| Estimated fat, per cent | | 16.0 |

values, the lower line to the thickness of skin and subcutaneous fat at the end of caloric restriction.

As this individual characteristic seemed to persist in the experimental subjects despite the changing nutritional status and the associated changes in the measured fat thicknesses (*i.e.*, in the absolute fat patterns), it may possess in "normal" individuals some permanence through time and thus provide means for a characterization of a relatively constant, genetically determined aspect of body "type." It should be noted that the amount of weight loss involved in the study referred to above was relatively small and the time short. Additional research on this problem is clearly indicated.

### (*d*) *Limitations*

The problem of fat distribution can be considered not only in terms of the distribution of the subcutaneous fat on the body surface but also in reference to the "external" (subcutaneous) and the "internal" fatty tissues associated with internal organs (*e. g.*, the perirenal fat) and the folds of the peritoneum extending into the abdominal cavity. The matter may be examined with profit by considering differences in skinfolds and in body density associated with aging. This should shed important light on the limitations of skinfold measurements as indicators of total body fat.

The data for a group of young and middle-aged men are given in TABLE 3. The groups were comparable in mean relative body weight (actual/standard weight for height, sex, and age). As one would expect, the skinfolds in the older group were, on the average, larger than in the younger men and the densities were lower. The large increase in the chest skinfold suggests changes in the distribution pattern of the subcutaneous fat, but consideration of the actual density of the older men (and the associated body fat, calculated according to Keys and Brožek, 1953) is more revealing. Using the prediction equation for density ($\hat{D}$), developed for young men (and the particular skinfold caliper, with a pressure of about 35 gm./mm.$^2$, reading in mm.),

$$\begin{aligned}\hat{D} = 1.0951 &- 0.00028 \text{ Abdomen}\\ &- 0.00073 \text{ Chest}\\ &- 0.00088 \text{ Arm}\end{aligned}$$

TABLE 4

RELATIVE BODY WEIGHT, AGE, AND FATNESS

Relative weight = 100 × actual weight/standard weight for sex, age, and height

| Weight category | A | B | C | D | E |
|---|---|---|---|---|---|
| Range of relative weight | below 85.0 | 85.0 to 49.9 | 95.0 to 104.9 | 105.0 to 114.9 | 115.0 and up |
| **Younger Men** | | | | | |
| Mean relative weight | 81.3 | 90.6 | 100.0 | 109.0 | 120.1 |
| N | 5 | 31 | 48 | 29 | 35 |
| Mean age (years) | 21.6 | 20.5 | 20.7 | 20.2 | 20.1 |
| Mean density | 1.0877 | 1.0808 | 1.0725 | 1.0689 | 1.0578 |
| Mean fat percentage | 4.9 | 7.4 | 10.4 | 11.7 | 15.5 |
| **Older Men** | | | | | |
| Mean relative weight | 80.0 | 91.0 | 100.3 | 109.0 | 120.0 |
| N | 22 | 21 | 35 | 31 | 16 |
| Mean age (years) | 52.4 | 52.0 | 51.7 | 53.1 | 51.4 |
| Mean density | 1.0560 | 1.0487 | 1.0415 | 1.0363 | 1.0330 |
| Mean fat percentage | 16.5 | 19.3 | 22.1 | 24.1 | 25.4 |

(see Brožek, 1954, p. 277), we obtain 1.0547 as the density *predicted* for the older men on the basis of their mean skinfold values, compared to the *actual* mean value of 1.0489. The corresponding fat values are 16.0 and 19.2 per cent of body weight. In other words, using the prediction equation derived for the younger men we would overestimate the density (and underestimate the total body fat). Although these differences are not very large in absolute terms, they are statistically reliable and may be interpreted as indicating that the deposition of internal fat in the process of aging proceeds at a faster rate than the increase of the thickness of the layer of subcutaneous adipose tissue.

A more telling example of the limitation of anthropometric data as indicators of body composition is provided by relative weight. The ratio of the actual to standard body weight is correlated positively with density and thus, in subsamples of a population homogeneous in age (and in physical activity), it may serve as a gross but acceptable criterion of leanness-fatness. Because the age correction is "built-in" into this index, older and younger individuals (as well as men and women) will differ markedly in density and in the calculated body fat (Brožek and Keys, 1950, 1953) at a given level of relative body weight.

The data, recalculated according to the Minnesota system, are given in TABLE 4. At both age levels there is about 10 per cent difference in body fat between the very light (Groups A) and very heavy individuals (Groups E). In the older men, roughly another 10 per cent of fat is added, reflecting the age changes in body composition.

### (*e*) *Development of Methods*

Dupertuis *et al.* (1951) noted that people differing in physique, as appraised from photographs, differ enormously in specific gravity (and the amount of estimated body fat) and that the "individual differences in specific gravity appear to depend primarily on varying degrees of the first component of physique (endomorphy), which is an anthropomorphic estimate of the amount of body fat." The description of physique followed Sheldon's system and technique of somatotyping. The subjects were 81 healthy young men (average age 26.5 years, range 18 to 48 years) selected to include representatives of extremes of body build. A positive correlation was obtained between specific gravity and the ectomorphy ratings ($r = +0.369$), and a negative correlation between specific gravity and endomorphy ratings ($r = -0.853$).

The sample, including a large number of subjects drawn from a highly selected group of naval divers as well as specially searched-for extremes of body habitus, is clearly excessively heterogeneous and does not represent any well-defined segment of the population. Nevertheless, the existence of a substantial correlation between specific gravity and the ratings of the round, soft aspect of physique is of definite interest.

At this laboratory, specific gravity values were obtained for 31 young men, measured and photographed under control conditions and after 24 weeks of semistarvation (Keys *et al.*, 1950). Two independent sets of ratings were made on inspection of pictures of the men in the nude, without reference to the subjects' nutritional status at a given time (Lasker, 1947). Both sets of ratings indicated a marked decrement in endomorphy at the end of the period of severe caloric restriction, slight decrease in mesomorphy, and a marked increase in ectomorphy. As in the study reported by Dupertuis *et al.* (1951), the coefficients of correlation between endomorphy ratings and specific gravity were negative (−0.716 for one investigator, −0.637 for the other set of ratings), and positive but somewhat lower between ectomorphy and specific gravity (+0.582; +0.601) (Brožek and Keys, 1952). Combining all the available information (2 sets of ratings for the 2 conditions), a prediction equation was calculated. The data, expressed in terms of densities and fat values estimated according to Keys and Brožek (1953) are given in TABLE 5. Although the sample again is heterogeneous in nutritional status, the size of the differences between the fat content associated with increasing endomorphy is remarkable.

In Sheldon's thinking (1954, p. 20), the assessment of an individual's somatotype should ideally approach the genotype "and by definition would take on a permanent identity." We are not concerned here with the problem of permanence versus variability of the somatotype. According to Sheldon (1954), the somatotypist should *take into account* the individual's nutritional record. He is still concerned with the stable somatotype, assigned after the effects of variations in nutritional status were partialed out. Wisely, he

TABLE 5

ASSOCIATION OF "ENDOMORPHY" RATINGS WITH BODY DENSITY AND ESTIMATED BODY FAT IN YOUNG MEN

| Endomorphy | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Density, gm./cc. | 1.0871 | 1.0790 | 1.0710 | 1.0629 | 1.0549 | 1.0468 | 1.0388 |
| Body fat, per cent | 5 | 8 | 11 | 14 | 17 | 20 | 23 |

comments that only a good longitudinal study can give us the answer concerning the *relative* permanence of a somatotype so conceived and defined.

Our concern and interest does not conflict with that of Sheldon. We wish to stress the *fact* that "endomorphy" ratings, made by competent investigators, including Sheldon's long-time associates (Dupertuis *et al.*), correlate with densitometric estimates of the fat content. The important point, I believe, is not what would be the correlation in more representative samples of the population than had been studied so far. What is needed is to develop a system of ratings and measurements of standardized photographs, consciously and directly focussed on the *variable* aspects of body build—the development of musculature and, particularly, of body fat. The more precise methods (densitometry, skinfold measurements, soft-tissue X rays) should be used for checking and improving the validity of the proposed system.

The comparison of body density values and of ratings of Sheldon's somatotype "components" brings out the need for a fundamental rethinking of the problem (both for the benefit of those who strive for the permanence of the somatotype as well as for those who are concerned specifically with variations and differences associated with diet, activity, age, and sex). A new approach to the description of human physique must be developed, based on the photographs but oriented toward anatomically defined body components.

### (*f*) *Interpretation*

At times, the examination of a problem by two or more methods facilitates a more correct interpretation of an observed relationship. Dependence of basal metabolism on body composition may serve as an example. On the basis of coefficients of correlation between data derived from soft-tissue X rays of the calf, it was concluded that together "muscle" and "fat" account for the major proportion (over 70 per cent) of the child's oxygen needs under basal conditions (Garn, Clark, and Portray, 1953). This statement is correct only in the statistical sense, in so far as the presence of the *association* between the width of the calf muscle and of "skin" (with the subcutaneous fat), on the one hand, and the basal metabolism, on the other hand, makes it possible to compare the variance of basal-metabolism values predicted ($\hat{Y}$) from the two criteria with the actual variance of basal metabolism ($Y$). The coefficient of determination ($r^2$) is defined as $r^2 = (SD_{\hat{Y}})^2/(SD_Y)^2$.

However, this fraction cannot be regarded as indicating the relative share of muscle mass and adipose tissue in basal oxygen consumption. This is clear on strictly logical grounds, as the existence of a statistical association, without additional evidence, cannot be interpreted as evidence of causation. The coefficient of determination is concerned strictly with variances of the predicted and measured values of basal metabolism. It throws no light on the partitioning of basal oxygen consumption among the organs and tissues of the body.

On the level of logical argumentation, the interpretation of a coefficient of determination ($r^2$) in terms of the share of a body comportment in basal metabolism may be clearly demonstrated as faulty by considering the correlations between some fractions of body water and oxygen consumption. As one could expect, all five fluid comportments examined by Wedgwood *et al.* (1953) correlated positively with basal metabolism, expressed as Cal./hr. The coefficients of correlation increased from $r = 0.49$ for plasma volume and $r = 0.54$ for intracellular fluid, through $r = 0.76$ for total body water, to $r = 0.80$ for both the extracellular fluid and the interstitial fluid, defined as extracellular fluid less the plasma volume. First, the last two compartments, measured in liters, are substantially different in absolute term, yet the coefficient of correlation is the same. Second, even though these compartments account statistically for 64 per cent of the interindividual variation in basal metabolism, they are metabolically inert and their actual participation in body's oxygen consumption must be close to zero. While the parallelism (due to the correlation with different measures of body size) is fairly close, no causal relationship in the physiological sense is involved at all.

The problem can be approached more positively on the basis of a physiological partioning of basal oxygen consumption (Brožek and Grande, 1955), based on the information on the rates of oxygen consumption in different organs and tissues, and on the mass of these tissues. Direct determinations of oxygen consumption from the rates of blood flow and the arteriovenous oxygen differences indicate that at rest the internal organs (notably liver, brain, heart, and kidneys) use up over 60 per cent of the total oxygen consumed. The share of the musculature is estimated at about 25 per cent of the total, with a range of uncertainty from about 15 to 28 per cent. Although no good estimate for the share of the adipose tissue is available at present, it can be only a small fraction of the remaining 15 per cent of total basal oxygen consumption that is not accounted for by the internal organs and musculature.

Examination of the problem of body composition and basal metabolism by the consideration both of the statistically established (external) relationships and of direct fractionation of oxygen consumption by methods of physiological analysis contributes to a sounder interpretation of the data. It is a good example of the benefits resulting from the integration of information obtained by different approaches to body composition and to the evaluation of its physiological significance.

## Summary and Conclusions

Human biology represents crossroads of several disciplines concerned with man's body structure and function. In human biology, thus defined, the study of the composition of the body represents one of the focal points. We have considered it primarily from the point of view of the *convergent methods*, contributed by anatomy, physical (somatic) anthropology, radiology (including both soft-tissue roentgenograms and evaluation of bone mineralization), biophysics, and biochemistry. Little attention was paid here to the assessment of the value of these methods in *divergent applications*.

Body composition, with its far-reaching theoretical implications, represents an important facet of dynamic anthropometry. We deal with a truly "dynamic" aspect of the human physique, characterized by large interindividual differences and the possibility of profound intraindividual alterations. It is understandable that, in an atmosphere characterized by a search for immutable "body types," such an inquiry might have lacked appeal.

In 1921 Matiegka proposed a system for the estimation of certain tissue masses on the basis of body measurements. However, his forward-looking proposals did not stir any more interest than, in their time, did Gregor Mendel's original papers documenting the fundamental laws of genetics.

Since 1940 important new tools have been developed for the assessment of body components. For research on man, body density, and measurements of total body water and its fractions proved to be particularly fruitful. The roentgenographic soft-tissue analysis was added to the anthropologist's tool box.

Although the latter techniques, particularly the densitometric and hydrometric analyses, are more elegant and more comprehensive, field research and a good deal of the work in schools, athletic fields, experimental laboratories, clinics, and physicians' offices must rely on the simpler anthropometric procedures.

The problems of synthesis of the techniques for the study of body composition were examined in reference to the internal consistency of different approaches: the "translation" of measurements (skinfolds) into roentgenogrammetric equivalents and prediction of total body fat from partial criteria of leanness-fatness; contribution of the different approaches to a more comprehensive description of human physique; evaluation of limitations of specific procedures and the need for the development of additional methods; and, last but not least, the value of a simultaneous application of two or more methods in terms of a sounder interpretation of the physiological significance of the data on body composition.

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# TOWARD AN ANTHROPOLOGY OF THE BRAIN

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Everybody, including writers of textbooks, admits that man owes his position in nature to his superior brain. But very few textbooks even mention that organ in their indices, to say nothing of their texts. The anthropology of the brain has hardly been begun. The reason may not be far to seek. Neurology has now become a highly specialized branch of anatomy that, in its present state of development, goes hand in hand with neurophysiology, so that the laboratory of a neuroanatomist often looks rather strange and forbidding, with its vacuum tubes and electronic equipment, among which the animal seems almost lost.

Still, it seems to me that a fair amount of work can be done without going too much into electronics, and the following outline tries to prove that point.

Let us first consider the brain of the primates. The relation of bodyweight and brainweight has interested science for many years, and the somewhat fanciful results of DuBois[9] have received wide publicity. I do not want to contribute further to a dissemination of wrong information by telling in detail his line of reasoning. Suffice it to say that he certainly arrived at wrong results, although they were undoubtedly very flattering to humanity and, perhaps, for that reason so acceptable. If we take all the primates and compute the regression of brainweight, $E$, on bodyweight, $S$, and throw this at once into logarithmic form, we obtain a formula which puts almost all the living forms on a straight line, and gives a high cephalization coefficient for this series. The formula is[5]

for primates: $$lg\, E = .79\, lg\, S - 1.00$$

for carnivores: $$lg\, E = .63\, lg\, S - .73$$

Of course, it is well known that a logarithmic formula will almost always give a good fit, but the fact that a human brain is as large as it actually is can be attributed, at least partly, to the circumstance that man is such a large animal. In addition to this, it is true, of course, that man's brain is very well developed.

We shall look at the brains of anthropoids a little closer, although we shall still confine ourselves to the outside, as it were. Let us look for a moment at the configuration of the ventricles. We shall compare a dog, a galago,[5] a tarsius,[7] cebus,[3] and a man.[15] The dog has an anterior and a posterior part to its ventricle. The galago has the posterior part so well bent around that it forms a clear temporal horn. The tarsius has no true temporal horn, but has a postero-superior prolongation that can be termed an occipital horn. Only from cebus on, the true primate pattern of anterior, posterior, and inferior horns is found. But since we are searching for patterns, it should be stressed that the pattern of the brain seems to be set as we come to the true primates, and that it is definitely foreshadowed both by the lemurs and by tarsius, although in a slightly different form by these two branches.

Thus, in the general configuration of the brain, all primates are somewhat similar. Wherein do they differ? It used to be thought that the frontal lobe of man was much larger than that of the lower forms. But when we trace the size of the frontal lobe in a diagram, as I did some years ago,[6] we find that in all primates it has about the same relative size. The differences are so small as to be, probably, no more than individual variations. Where man differs considerably from his lower relatives is in the development of his parieto-occipito-temporal lobe, which is much larger than that of any other member of the primate group. The development of large areas of association, as Flechsig[11] called them, may have been of profound importance to man. In the monkeys, even in the apes, the various sensory areas are fairly close together, so that there cannot be too much working over the sensory input. In man, there is considerable space, and that may well make an enormous difference in the type of sensation that actually comes to consciousness. That it is not the sensations as such that come through is obvious, especially from all the data that the Gestalt school has brought to light. The various illusions point in the same direction.[12]

It might be of some interest to follow the changes that the olfactory apparatus undergoes during primate development. The olfactory brain now comprises the olfactory bulbs, the anterior olfactory tubercle, the prepyriform area, and part of the amygdala,[1] but not the cornu ammonis, nor all those regions in the posterior part of the brain that traditionally used to be considered rhinencephalic. The lowly ancestors of the primates, the tupaias and other insectivores, have a fairly large olfactory brain.

We cast a glance now at tarsius. This animal, in spite of its enormous visual area, has also a considerable portion of its brain given over to olfaction. The olfactory brain is definitely larger in tarsius than it is in true primates. Even in galago, the smell brain is larger than it is in higher primates, although it is not as large as in tarsius. While the shift to optic impressions as the most important clue to the outside world started in tarsius, it got well under way only in the lemurs and achieved its definite status in the true monkeys. Unfortunately, we have not yet any quantitative data, although it should not be too difficult to get them.

When we try to compare human races, we come to very insecure ground. We know very little about anything. Let us start with the brainweight. We have that of several races, and the pertinent data have been assembled (Bailey and von Bonin[2]). That there are differences between the different races seems beyond doubt, but what do they mean? It would be of great interest to compare the brainweight with the bodyweight but, unfortunately, the necessary data are not available. So we are left with the fact that the brain has different weight in different races, but whether that reflects actual differences or the vagaries of the weighers, is almost more than we can say. As the table stands, it certainly makes no sense whatever, and subjective rather than objective differences cannot be ruled out.

It would be of great interest to determine whether the various parts of the brain showed racial differences in their development and, with the modern methods of encephalometry,[4] that could be done without too great difficulties. We need samples of about 25 to 50 brains of each race, and it should not be too hard to get them, particularly when it is borne in mind that the brains are not destroyed for other uses by encephalometry. The question of the parietal lobe is particularly intriguing and, for a first survey, it seems quite permissible to consider everything behind the central sulcus as parietal lobe, or, if you prefer, parieto-occipital lobe. For in man, the striate area is almost completely on the medial side, and the parastriate and peristriate areas can be considered part of the parietal lobe.

The question whether there are any differences in the frequency with which various sulci, or variations of these, appear in different races is, of course, of interest and has led indeed to numerous investigations. Unfortunately the investigations are spotty, and often the definitions are none too clear. The famous lunate sulcus is a good example. Lots of differences have been found, but it is almost impossible to correlate these with race or with anything else. Many of the results undoubtedly tell more about the investigator than about his objects.[2]

Whether there are any histological differences is again a moot question. We have some "information" about the Madurese, but it is so fanciful as to be valueless (van Noort[14]). The information is based on only a few brains, and reflects the state of preservation of these brains much more than actual differences. To do this work by hand is next to impossible in any case. But the Guggenheim Foundation has given me a grant. With its help I am now engaged in constructing photoelectric equipment with which to scan the cortex for the cell/gray coefficient. This should be done in a reasonable time, so that data for the determination of racial differences may be available in the not too distant future. Of course, a lot of preliminary observations will have to be made on the changes brought about by age, sex, perhaps by the fixation, *etc.* But all this, clearly, can be done with the means now at our disposal.

We finally may ask some more pertinent questions, as it were, and the question of the development of the brain after the evolution of articulate speech is, of course, the first that comes to mind. This question is still far from being solved. Broca's and Wernicke's ideas on the subject are almost certainly wrong, and it is only very gradually that saner views begin to prevail. Conrad[8] has published diagrams of brain that show the topographical position of all the injuries that led to motor aphasia and of all the injuries that led to sensory and amnesic aphasia. I think this brings out two points: the very wide spread of the lesions over a large part of the cortex, and the fact that the two maps are almost complementary to each other; in other words, that the motor ability to speak can be interfered with from different parts through the ability to understand the spoken word. That fairly large parts of the brain are involved is also easily understood. From these observations, we certainly get an impression of the organization of the brain that is far from the classical one. There is not the strict localization that Broca and Wernicke assumed, but the cortex is much more equipotential, although that, again, is not quite correct but errs in the opposite direction. Moreover, to equate the regions from which speech can be disturbed with those in which it originates is not correct, therefore the regions that we need when we speak may be much smaller than those from which we can disturb it. It may well be, *e.g.*, that the large region of the pyramidal tract is involved only in a suppressing activity, and that the patient refuses to speak after a pyramidal lesion simply because it would involve him in two great difficulties. The fact that, on the other hand, the motor fields for the face, the arm, and the leg overlap much more than the clean-cut diagrams would make us believe is clear from all the maps that have been published.[16]

It is interesting that aphasia develops quite differently in small children and in adults. During learning, the cortex obviously undergoes changes that might be likened to a process of crystallization.

Most movements of the body are under the influence of the proprioceptors for the correct execution: the whole melody of movement is built on the steering by the myotactic reflex.[13] In speech, there is no such thing. The laryngeal muscles are, as far as we know, without proprioceptors, and any steering that occurs (speech must be steered in one way or another), comes about by the acoustic impulses. It is only by hearing the sounds we produce that we become aware of their correctness or falsity. This steering is nonexistent in deaf children, hence their inability to speak. To develop this ability to steer the motor apparatus for speech is a very difficult achievement, and it is from this point that the long evolutionary history of speaking can be partly understood.[10]

But speech is based, after all, on a very detailed synergy between larynx, oral cavity, and lips, and these three apparatuses have to work together in a very precise manner. How that is done neurologically is not clear. It should be remembered that the vagus, which moves the larynx, and the trigeminus, which moves the lips, are both branchial muscles, while the hypoglossus, which moves the tongue, is a somatomotor muscle. The only place where these three muscles are tied together, as it were, is in the cortex.

Quite apart from these considerations, however, the larynx in most quadrupeds is not in a proper position to make the mouth cavity resound. It is frequently said that the larynx is just the same in tetrapods as it is in man. That is probably true in a narrow sense of the word, but it is not true when we consider the position of the larynx in the oral cavity. In most quadrupeds, and that includes the lemurs, the larynx is shoved way upwards into the pharynx, so as to come into close contact with the soft palate and shut itself off almost completely from the mouth. That has its great advantages, *e.g.* in a grazing animal that relies on its sense of smell for the recognition of enemies. The food, once in its mouth, will not smell and the animal is able to smell its enemies even when feeding. With the advent of upright posture, the distance between larynx and soft palate gradually increased until the human stage was reached, in which the larynx opens into the oral cavity and speech as we know it thereby becomes possible.

Much of the work that has to be done on the evolution of speech will be done on the peripheral organs, which are not as well understood as they should be. But apart from that, we shall have to repeat what Broca said almost

100 years ago: first we have to know what to localize before we can hope to localize it. In the case of speech, that is not as simple as we might have thought some time ago. Nevertheless, there seems ample room for an anthropology of the brain, if only we make a serious effort.

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# LONGITUDINAL ANTHROPOMETRIC DATA IN THE STUDY OF INDIVIDUAL GROWTH

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The title of this paper calls for discussion of a particular form of data in the study of a specified type of problem. Succinctly, the task assumed is that of directing attention to certain methodologic matters regarding the use of longitudinal data* in the investigation of human morphologic growth processes.

It is a requirement of efficient and fruitful scientific study that the gathering and analysis of data receive explicit and critical consideration in relation to the problem the data are intended to subserve. "Research is the scientific method of finding the answers to questions";[51] a scientist's first responsibility is "to know precisely what is to be investigated, to formulate the problem as accurately as possible."[17] Primary next steps are those of "determining what data will need to be collected, the manner in which they will be collected, and the method by which they will be analyzed."[10]

The relevance of this association between the nature of the problem and the specifications of data collection and analysis warrants a little directed elaboration. Anthropometric data amassed to obtain an estimate of a population mean (say one accurate within 2.0 mm. at the 1 per cent level of confidence) do not necessitate measurement procedures of the order required to obtain like estimates for individuals at the same confidence level.[36] Again, measurements made to represent morphologic status (*e.g.*, the length of segment $A$ at age $Y$) call for less demanding reliability standards than measurements made for the purpose of registering morphologic velocity (*e.g.*, increase or decrease in the length of segment $A$ between ages $Y$ and $Z$).[52] Stated more generally, it is less difficult to reduce chance error within adequate bounds where the problem pertains directly to measurements (*e.g.*, somatic trait description at one ontogenetic age or stage) than where the problem necessitates data in the form of derived measures (such as size changes and form indices)[55] or time series (as for the study of morphologic trend and departures from trend in individuals).[48]

With reference to individual organisms, data collected cross-sectionally (each organism examined at one age only) are useful solely for depicting state or status or stage attained. An advantage of the longitudinal method of data accumulation (each organism examined at two or more ages) lies in the fact that individuals may be portrayed more comprehensively, *i.e.*, with respect to status, short-term velocity or growth rate, and long-term trend or pattern.[48, 53]

Curves drawn to measures of central tendency do not afford an incisive understanding of growth processes or lead to discovery of relations between processes. Until central tendency trends have been compared with individual trends, it is not known what meaning they have biologically.[18, 41] It follows

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* Also called time series[48] and seriatim records.[46]

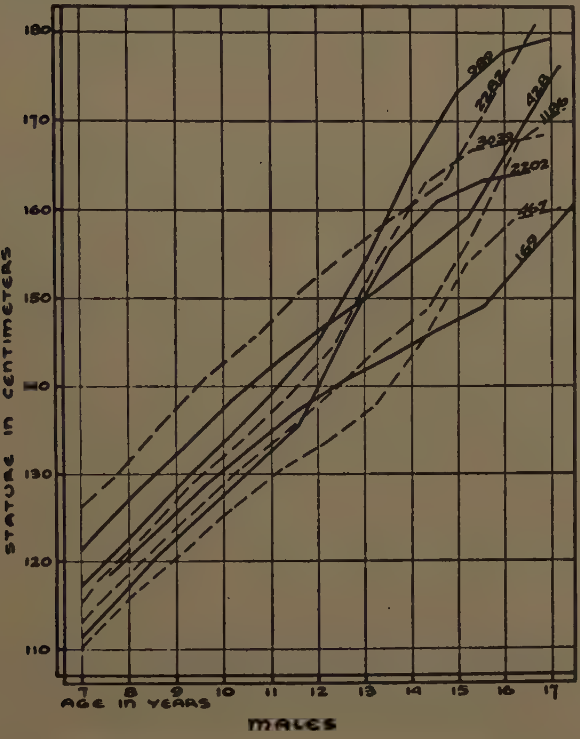

FIGURE 1. A series of individual stature curves for North American white boys. Reproduced from Meredith.[25]

that those who study human growth should chart a course between average curves that confound morphologic processes and individual curves in which morphologic processes cannot be disentangled from measurement errors. This is a difficult and time-consuming course, yet one facilitated by the investigative soundings of earlier navigators. It is the course of high-caliber longitudinal research.

### *Methodologic Lessons from Early Studies of Individual Growth*

*On extrapolation.* The collection of longitudinal records for studying many patterns of human growth takes years of time. Statistics on subject loss in long-term programs attest further to the great patience that research of this type entails. It appears that early workers, in their enthusiasm to contribute as fully as possible to the meager knowledge of the day, sometimes resorted to extrapolation.

Baldwin's 1914[1] and 1921[2] publications are of prime historical importance. Those parts of both reports that deal with individual growth in stature during the school years have influenced a large number of investigators, teachers, and writers. Baldwin amassed substantial support for the generalization that between the childhood ages of 6 and 11 years "each boy holds approximately his relative position in the group"[1] or, alternatively expressed, "the curves assume a railroad appearance . . . with little crossing."[2] This portion of Baldwin's research has been confirmed. Correlation coefficients for stature at age 6 years with stature at age 10 (girls) or 11 (boys) years approximate $r = .95$.[23, 58]

The generalization was extended through the adolescent years. In a 1922 paper, Baldwin wrote: "The boy that is tall at 7 will be tall at 14 and 16 and 18; and the boy that is short at 7 as a rule will be short at 14, 15 and 16, and so on."[3] Here, the foundations were much less secure. The number of curves extending through adolescence was smaller, while the frequency and extent of interindividual displacement ran appreciably higher. There seems little doubt that one component that entered into this wider generalization was extrapolation. A succession of recent studies has demonstrated: "Boys that are 'tall' or 'short' between 7 and 11 years may be 'medium' at 14 or 17 years, and boys that are 'medium' from 7 to 11 years may be either 'tall' or 'short' at 14 or 17 years."[25] Correlation coefficients for stature at 12 (girls) and 14 (boys) years with stature at 18 years approximate $r = .65$.[49] FIGURE 1 presents a series of individual stature curves for boys—attention is called to the "railroad appearance" from 7 to 11 years and the "marked crossings" between 11 and 17 years.

There has been extrapolation backward as well as forward. In a 1931 monograph, Wallis stated: " . . . tallness and shortness of adult stature is present *in the young child*, and if strong factors of retardation or acceleration do not appear to change the natural course of growth, the individual, year by year, will maintain very nearly the same position in relation to his age, sex, race and economic group."[56] Data recently reported by Low[19] show that correlation coefficients for stature at birth with stature at 5 years of age approximate $r = .30$ on each sex. Other studies have found the association between neonatal stature and stature in late infancy to lie near $r = .50$.[26, 50]

The lesson is clear. For those engaged in the slow moving task of amassing and analyzing long-term sequences of individual growth, "too extensive generalization is one of the dangers."[48] Do not extrapolate.

*On truncation.* Human ontogeny encompasses several decades. Where seriatim data on morphologic processes have been obtained, they have covered chronologic periods rarely exceeding one decade. This segmental approach is convenient and often adequate.[4] There are, however, biologically important considerations that condition the usefulness of subdividing ontogeny into age segments. Early workers, apparently anxious to proceed with analysis of their longitudinal records, sometimes made insufficient allowance for individual differences in the timing of morphologic events.

Baldwin[1, 2] grouped his series of individual stature curves on school age children into two classes. One class included trends showing "rapid acceleration during adolescence" and the other those approximating "uniformity of increase through adolescence." Later research has confirmed the "acceleration" type, but not the type with "relatively uniform" rate of increase throughout late childhood and adolescence resulting in a trend that is "practically a straight line." From analysis of more than 500 individual stature curves accumulated at Harvard University and the State University of Iowa, Meredith has found what Baldwin termed the "acceleration" pattern of circumpuberal growth "to occur with 100 per cent frequency" in boys and almost the same frequency in girls.[25]

In considering how it happened that the "straight line" type of circumpuberal stature trend was introduced into the literature on human morphology, the possibility that truncated trends were accepted for analysis presents itself with persistency. Those curves classified as linear probably did not extend throughout adolescence. In other words, it appears likely that the upper end of the age range for beginning of the circumpuberal acceleration was underestimated. For example, classification might have been made on the assumption that individuals giving no evidence of circumpuberal stature acceleration by 15 years of age would not show acceleration after that age. See FIGURE 2.

Another example of truncation is found in a study by Davenport[7] reported in 1935. Individual growth curves for shoulder width (biacromial diameter) extending from about age six years to varying ages in the second decade were classified on the basis of general form into three groups. Two of these type-groups were designated "concavo-convex" and "shallow U-shape." The former subsumed trends that were "concave above" prior to the age at which the peak of the circumpuberal acceleration was reached, then "convex above" into early adulthood. The latter (type "shallow U") appears to represent

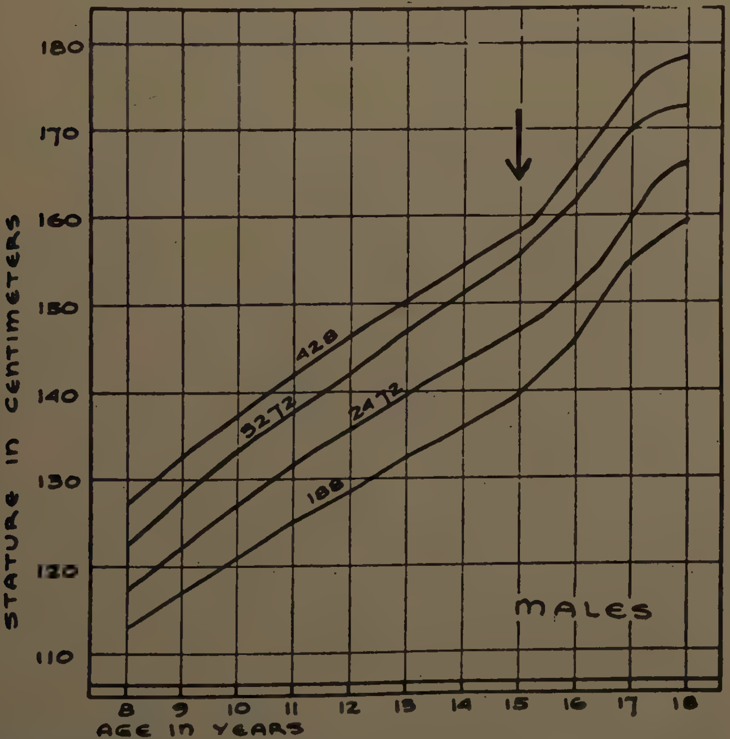

FIGURE 2. Stature trends for four boys showing circumpuberal acceleration after 15 years of age. Reproduced from Meredith.[25]

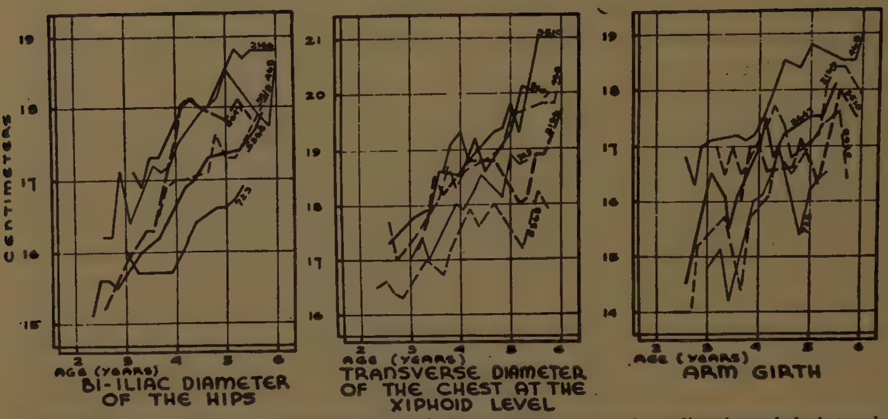

FIGURE 3. Grids illustrating the importance of reducing measurement error in studies of morphologic trend and oscillation. Reproduced from Knott.[15]

nothing more than truncated concavo-convex trends. Davenport's discussion included the comment that these curves "may be regarded as uncompleted examples" of the concavo-convex type. To categorize as two "types of growth" trends that represent one morphologic pattern can be misleading and, at best, constitutes sterile analysis.

Again the lesson is apparent. Early research has marked with warning the pitfall of truncation. Guard against truncations that lead to misconceptions regarding intraindividual processes, or to classifications that violate the principle of parsimony.

*On measurement error.* In the literature on human morphology, it frequently is stated that the individual child "grows by fits and starts";[5] that growth "is intermittent or spasmodic"[16]—"proceeds in a jerky irregular manner"[47]—"takes place in waves"[57]—"consists of alternate intervals of acceleration and retardation"[8]—"proceeds in spurts."[13] * These statements give rise to a basic scientific question: To what extent are such statements morphologically sound and to what extent do they reflect random error in measurement?

Early anthropometrists gave particular attention to the standardization of instruments, the definition of landmarks, and directed laboratory experience. In this sense, they recognized the importance of precision in data collection. In his 1920 manual, *Anthropometry*, Hrdlicka wrote: "Precision is a matter of well tested instruments, of good instruction, and . . . of minute care."[14] There was no reference whatever to reliabilities under specified conditions, and no discussion of graduated procedures through which chance error could be geared to the demands of the problem. Long-term anthropometric programs looking toward the elucidation of individual growth began in this setting. Seriatim measurements were accumulated with care, but their reliabilities were not determined and appraised for adequacy.

The historical consequence was a period of low return on longitudinal investment. Individual curves were found to show numerous fluctuations;

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* For a discussion of this view with respect to cross-sectional analyses, see Meredith, H. V.[29]

persons responsible for their analysis confronted the difficult problem of distinguishing between morphologic oscillations and the random fluctuations of unreliability. Some ignored the problem, others considered it insurmountable. Publications around 1935 by Davenport[7] and Meredith[22] are illustrative. Meredith, after examining five series of Cartesian grids for individual boys 6 to 18 years of age, took the position that the curves for "bi-trochanteric diameter, thoracic circumference, body weight and breathing capacity" were too irregular for meaningful analysis. (Figure 3, taken from a monograph by Knott,[15] presents similarly irregular curves for width of thorax, width of hips, and girth of arms.) Davenport, on the other hand, examined a series of curves for bi-iliocristal diameter and grouped them in four classes. Two of these classes were designated "intermittent type" and "wave type." It was left for the reader to pose the question of whether the classes represented morphologic processes or an ordering of unreliability manifestations.*

A third lesson stands in relief. The collection of data for the study of individual growth processes is a technically demanding task. This especially is true if one wishes to determine whether there are short-term morphologic undulations about the long-term trends. Do not amass longitudinal records until it is known that chance error will be minimized satisfactorily.

### *Research Pertaining to the Collection of Morphologic Time Series*

This and the succeeding section deal with studies relating to the morphologic growth of individual children carried out over the past 20 years at one center, the State University of Iowa at Iowa City, Iowa. Investigations designed to assure the fruitful gathering of anthropometric data for longitudinal research are drawn upon below. The following section will present sample findings on individual increments and childhood growth patterns obtained through the use of high collection standards.

*Direct measures.* In 1935, following trial analysis of the seriatim data accumulated during the period 1920–1934, it was recognized that few of these data (principally those for stature) could be used in the investigation of problems of individual growth.[22] This recognition led to a series of studies aimed at providing a more adequate methodologic foundation for utilizing direct measurements on children to obtain individual trends of change in body size and form.

Over the years from 1935 to the present, reliabilities have been investigated for 5 quantitative indices of body form and more than 30 external dimensions of the body. For many measures, work has been done at several ontogenetic stages: Goodman[12] obtained reliabilities on neonates; Knott,[15] on children 3 to 6 years of age; Meredith[24] and Marshall,[20] on boys 8 and 9 years of age; Newcomer and Meredith[43] and Trim and Meredith,[55] on boys 15 years of age. The most comprehensive study was that by Knott. It encompassed 11 transverse and anteroposterior diameters, 10 length and height measurements, 9 circumferences, and 5 measures of thickness of skin and subcutaneous tissue. For the studies as a group, the model stipulated: (1) specification of each

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* Some definitive findings on this question[33] will be discussed at a later point.

TABLE 1

ANTHROPOMETRIC RELIABILITIES ON 15-YEAR-OLD BOYS*

| Measurement | Standard deviation of differences ($\sigma_d$) | Reliability coefficient ($r$) |
|---|---|---|
| Body weight (kg.) | 0.06 | .999 |
| Leg girth (cm.) | 0.08 | .996 |
| Hip width | 0.09 | .994 |
| Arm girth | 0.14 | .997 |
| Stature | 0.25 | .996 |
| Stem length | 0.28 | .996 |
| Upper limb length | 0.29 | .992 |
| Lower limb length | 0.29 | .991 |
| Shoulder width | 0.32 | .981 |
| Abdomen girth | 0.64 | .986 |
| Chest girth | 0.68 | .985 |

* Reproduced from Newcomer and Meredith.[43]

procedure with reference to position of subject, landmarks, instrument, and details of method; (2) strict independence of measurements; (3) examination of records for systematic error; (4) analysis of chance variation by both the difference approach and the correlation approach; and (5) appraisal of the magnitude of measurement error in relation to the magnitude and growth rate of the particular dimension. A sample from the results is given in TABLE 1.

Following the 1936–1938 reliability investigations of Knott, Marshall, and Meredith, a new program of longitudinal research was initiated. This program required, and has continued to require, that: (1) at every examination of a child, all of the direct body measurements included must be taken by two different anthropometrists; and (2) where the results of the two anthropometrists are not in close agreement, each must make a second measurement. Illustrative of the criteria for "close agreement" (derived from the reliability findings) are the following: agreements within 0.1 cm. on biparietal diameter, bi-iliocristal diameter and leg girth; 0.2 cm. on stature, arm girth, and foot length; 0.4 cm. on biacromial diameter, stem length, and girth of thorax. It need not be labored that averages derived from the two or four measurements secured under these provisions constitute values that closely approximate "true" morphologic measures. Later, some returns will be exhibited from application of this degree of anthropometric rigor to problems of growth increment and growth trend.

Those contemplating time-series research on changes in body form will be interested in the Trim-Meredith study[55] on dependability of anthropometric ratios. Reliabilities were compared for ratios based upon measurements by one anthropometrist, and ratios where the basic data were averages of independent measurements by two anthropometrists. Under the latter procedure, improvements in ratio consistency as high as 20 per cent were obtained for shoulder width in percentage of hip width, and girth of thorax in percentage of girth of abdomen. See TABLE 2.

*Secondary-source measures.* In 1946, under the joint sponsorship of the Iowa Child Welfare Research Station and the Department of Orthodontics,

TABLE 2

RELIABILITY STATISTICS FOR FIVE ANTHROPOMETRIC RATIOS ON BOYS 15 YEARS OF AGE*

| Ratio | N | Type of basic measures | | Increase in consistency |
|---|---|---|---|---|
| | | Single | Composite | |
| | | *r* | *r* | % |
| (Leg girth × 100/Lower limb length) | 102 | .986 | .997 | 8.9 |
| (Arm girth × 100/Upper limb length) | 102 | .979 | .989 | 5.6 |
| (Chest girth × 100/Stem length) | 102 | .963 | .981 | 7.5 |
| (Shoulder width × 100/Hip width) | 102 | .908 | .976 | 20.1 |
| (Chest girth × 100/Abdomen girth) | 102 | .850 | .956 | 23.3 |

* Reproduced from Trim and Meredith.[55]

the scope of the longitudinal research program was expanded. This expansion placed greater emphasis on investigating postnatal growth in the calvaria and face. In addition to direct measures, measures were needed from lateral and posteroanterior roentgenograms of the head and casts of each dental arch. As a consequence, new problems of reliability and validity presented themselves. From the standpoint of reliability, there was the matter of adequately minimizing both the random error in securing the secondary sources (roentgenograms and casts) and the random error in obtaining data from these sources. With respect to morphologic relevance, there was the task of determining, and correcting for, systematic distortion in the roentgenograms and casts.

Studies pertaining to radiographic distortion and the reliability of measures from roentgenograms have been made by Potter and Meredith[44] and by Mindeman.[42] The former also dealt with the comparative reliability and validity of two dimensions obtained (1) by radiography, with the aid of a head positioner at a distance of 60 inches from the X-ray source; and (2) by direct measurement of the child. Findings led to the recommendation that data for biparietal diameter be taken by direct measurement, and that data for bigonial diameter be derived from the standardized posteroanterior roentgenogram.

Meredith and Cox[34] and Meredith and Hopp[38] have investigated the reliability and validity of measures of dental arch width obtained on stone casts made from alginate hydrocolloid impressions. The Meredith-Hopp study focused attention on maximum rectilinear distance between the buccal surfaces of the deciduous second molars; the Meredith-Cox study on maximum interbuccal and minimum interlingual diameters at the permanent first molars. Measurements were made to the nearest 0.1 mm. Both studies obtained correlation coefficients, specific for sex-arch-age subgroups, of the order $r = .99$; both found the difference between independent measurements by persons trained in dental cast anthropometry to lie between 0 and 0.2 mm. with the probability of 19 to 1. Evidence that the various procedural stages from child to dental cast were sufficiently efficient to approximate morphologically valid reproduction was derived by the method of securing certain conveniently obtainable measurements directly in the mouth, and comparing these with measurements on corresponding casts. Means for a given dimension measured several times each way showed no systematic variation.[34] Additional projects on technical aspects of gathering quantitative seriatim data through the media of casts and roentgenograms are in progress.*

*Measurement efficiency.* Efficiency of data collection in a longitudinal research program has other facets than those already cited. In the study of certain problems, it is necessary to control successive examinations for non-morphologic factors (*e.g.*, the influence of variation in bladder and bowel content on increments for body weight) and factors related to the plasticity of the organism (*e.g.*, the influence of length of time in the vertical position on increments for erect stature). Redfield and Meredith[45] measured the erect stature and sitting height of four-year-old nursery school children before and after an afternoon nap period. The mean changes associated with this interval of recumbency were found to be "equal to two months' growth." It follows that seriatim measures of these dimensions, especially if taken on young children at less than annual intervals, should be made with time since sleep or rest in the recumbent position held roughly constant.

For problems such as the analysis of increment trends and the construction of increment norms, efficient data collection involves securing measurements at equally spaced intervals. An increment distribution for the period six to seven years requires basic data on a sample of children at, or quite close to, each of these ages. The analysis of individual curves drawn to semiannual increments presupposes the availability of seriatim measurements at or near regular half-year intervals. These needs are facilitated by a carefully kept appointment register, and a person assigned to strive for precise scheduling of examinations. In our program, initial appointments are scheduled within three days of each child's birthdate. Subsequent examinations are at quarterly (below five years of age) and semiannual intervals, these also being exact to within a few days. This standard is practicable; deviations have been rare except on occasions of illness.

It is pertinent, in time series research, to inquire into the frequency with which repeated measurements serve a useful purpose. Some morphologic measures can be determined more reliably than others. Also, some portions of the body change more rapidly than others. Recognition that anthropometric reliabilities differ, and growth rates differ, suggests the hypothesis that in the study of individual growth processes new observations are obtained profitably at intervals that vary from trait to trait. Quantitative materials supporting this have been presented in investigations by Meredith,[24] Marshall,[20] and Knott.[15] Differential "measurement frequency" schemata were developed in these studies on the assumption that observations of individual growth are of value at intervals such that the mean increment for a dimension equals 90 per cent of the differences between independent (reliability) measurements for the dimension. TABLE 3 illustrates the approach. The main inference to be drawn is that in longitudinal programs it usually is inefficient to measure every trait under study at each examination. A staggered schedule of the measures

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* For exceptionally fine work on a widely used secondary source not considered here—the standardized photograph—see Tanner and Weiner[64] and Dupertuis and Tanner.[9]

TABLE 3

RELATIONSHIP BETWEEN ANTHROPOMETRIC RELIABILITIES AND GROWTH INCREMENTS FOR 8- AND 9-YEAR-OLD BOYS*

| Dimension | Mean annual increment | Reliability criterion | Estimated maximum frequency of measurement |
|---|---|---|---|
| | *mm.* | *mm.* | |
| Stature | 54 | 7.5 | Bimonthly |
| Bi-iliocristal diameter | 8 | 1.5 | Quarterly |
| Girth of leg | 10 | 2.6 | Quarterly |
| Bitrochanteric diameter | 10 | 3.3 | Quarterly (?) |
| Sitting height | 21 | 7.8 | Semiannually |
| Thoracic circumference | 22 | 9.1 | Semiannually |
| Girth of thigh | 16 | 7.8 | Semiannually |
| Forearm girth | 6 | 3.2 | Semiannually |
| Arm girth | 7 | 3.9 | Semiannually (?) |
| Bicondylar diameter of femur | 2 | 1.3 | Annually |
| Biacromial diameter | 10 | 10.3 | Annually |
| Bicondylar diameter of humerus | 1 | 1.7 | Biannually |

* Reproduced from Meredith.[24]

to be taken in consecutive examinations helps offset the time required for attaining high precision on the items included.

It would be inept to terminate a discussion of measurement efficiency in longitudinal research without referring to the crucially important matter of maintaining satisfactory reliability standards once they have been attained. This is an ongoing task that calls for constant vigilance and rigorously objective teamwork. Our laboratory, over the years since 1937, has operated with (1) a written statement specifying in detail each technique employed—this is supplied to all anthropometrists during their training period; (2) planned rotation of members of the two-person anthropometric teams; (3) provisions for avoiding systematic differences in procedure at ages where one sex is measured by women and the other by men; and (4) frequent occasions of both solicited and unanticipated spot checking.

### *Recent Findings on Individual Growth*

At this writing, only a fraction of the longitudinal morphologic data accumulated from 1937 has been analyzed. It is possible, however, to cite several series of findings on human growth obtained through use of the collection procedures discussed in the foregoing section. All findings pertain to North American white children.

*Increment and ratio norms.* Annual increment distributions have been described by Meredith[31] for bizygomatic diameter over the age span 4 to 10 years, by Carl[6] for stem length over the age span 5 to 9 years, by Meredith and Carl[33] for bi-iliocristal diameter over the age span 5 to 9 years, by Meredith[32] for lower limb length and leg girth over the age span 5 to 11 years, and by Meredith and Meredith[39] for a set of 10 measures over the age span 4 to 8 years. TABLE 4 reproduces the normative results for one age interval from the most comprehensive study of this group.

Increment distributions representing longer periods have been described for

TABLE 4

ANNUAL INCREMENT NORMS FOR 10 MEASURES OF PHYSICAL GROWTH ON WELL-NOURISHED NORTH AMERICAN WHITE CHILDREN OF BOTH SEXES*

| Measurement | Small gain | Moderately small gain | Average gain | Moderately large gain | Large gain |
|---|---|---|---|---|---|
| *Age 4 to 5 years* | | | | | |
| Weight (lbs.) | Under 3.2 | 3.2–4.2 | 4.3–5.8 | 5.9–7.3 | Over 7.3 |
| Stature (cm.) | Under 6.0 | 6.0–6.4 | 6.5–7.4 | 7.5–8.0 | Over 8.0 |
| Length: stem | Under 2.2 | 2.2–2.5 | 2.6–3.1 | 3.2–3.5 | Over 3.5 |
| Upper limb | Under 2.7 | 2.7–2.9 | 3.0–3.6 | 3.7–4.0 | Over 4.0 |
| Lower limb | Under 3.3 | 3.3–3.7 | 3.8–4.4 | 4.5–4.9 | Over 4.9 |
| Width: shoulders | Under 0.7 | 0.7–1.0 | 1.1–1.5 | 1.6–1.9 | Over 1.9 |
| Hips | Under 0.6 | 0.6–0.7 | 0.8–1.1 | 1.2–1.3 | Over 1.3 |
| Girth: chest | Under 0.3 | 0.3–0.9 | 1.0–2.0 | 2.1–3.0 | Over 3.0 |
| Arm | Under −0.1 | −0.1–0.1 | 0.2–0.6 | 0.7–1.1 | Over 1.1 |
| Leg | Under 0.3 | 0.3–0.5 | 0.6–1.1 | 1.2–1.6 | Over 1.6 |

* Reproduced from Meredith and Meredith.[39]

biparietal diameter,[30] bizygomatic diameter,[31] maximum interbuccal width of each dental arch at the deciduous second molars,[38] upper limb length,[28] bi-iliocristal diameter,[33] stem length and lower limb length.[6] The stem and lower limb study dealt with percentage increments for biennial periods between 5 and 9 years, the bi-iliocristal study with percentage increments for biennial and quaternary periods between 5 and 9 years, the upper limb study with absolute and percentage increments for biennial periods between 4 and 10 years, the arch width study with absolute increments for the quaternary period 4 to 8 years, the study of upper face width with absolute increments for quinquennial and decennial periods between 3 and 15 years, and the biparietal study with absolute increments for biennial periods between 5 and 9 years.

Some beginning steps have been taken in the construction of frames of reference for investigating body form and quantitatively determining the degree to which children, from age to age, maintain and/or change their positions in the peer group. Meredith and Culp[35] and Meredith and Sherbina[40] published variability norms for three anthropometric ratios covering the age period 4 to 8 years. These norms describe slender-to-stocky continua representing the upper limbs, lower limbs, and body stem, respectively. It is of interest that correlation methods revealed low positive associations between stockiness of the body stem and stockiness of each limb, and only moderate positive associations between upper limb stockiness and lower limb stockiness.

Trim and Meredith[55] constructed anthropometric ratio norms at age 15 years for three continua of the "slender-to-stocky" class and two continua of the "regional-predominance" variety. The former were the same as those studied above, *i.e.*, ratios of girth to length for the stem, upper limb, and lower limb; the latter portrayed the relations of shoulder width to hip width and chest girth to abdomen girth. Meredith and Higley,[37] incidental to appraising a claimed relationship between upper face width and palate width, described distributions from orthodontically normal children five and seven years of age for the ratio of maxillary arch width at the deciduous second molars to bizygomatic diameter.

*Increment relationships.* Correlation between size at selected ages and gain over subsequent periods has been investigated by Carl,[6] Meredith and Carl,[33] Meredith,[32] and Meredith and Hopp.[38] Carl studied stem length at age five years in relation to gain in stem length between five and nine years, Meredith and Carl studied bi-iliocristal diameter at the same age in relation to gain over the same period, Meredith studied three lower limb variables at age 5 years in relation to changes in these variables over the period 5 to 11 years, and Meredith and Hopp studied widths of the maxillary and mandibular dental arches at age four years in relation to changes in each width between four and eight years. The findings varied from no statistically significant association to moderate positive relationship, *i.e.*, the *r*'s were near .50 for lower limb length, near .40 for leg girth, near .30 for stem length and hip width, and practically zero for the arch widths and the ratio of leg girth to lower limb length.

Meredith[32] has investigated the association between change (gain or loss) during a given period, and change during a subsequent period of equal duration. The measures analyzed represented ages 5 to 8 years and 8 to 11 years, and were for lower limb length, leg girth, and the ratio of the latter to the former. Pearson coefficients approximated $r = .55$ for the measures of size and $r = .30$ for the measure of form.

Two studies have been made on the relation between increments of growth over a half-year period and illness history. Martens and Meredith[21] obtained increments for nine morphologic traits on five-year-old nursery school children measured in the fall of the year, and exactly six months later. They also secured day-to-day information on absence from school for illness. Correlation of increment values with days of illness gave $r = -.02$ for stature, $r = .05$ for weight, and coefficients of the same order for the other measures. A later study by Evans[11] compared increments over a fall-to-spring period of six months on another sample of nursery school children separated into health classes. These children were three- and four-year-olds placed on the basis of their illness records into one of the following categories: (1) healthy, (2) mild respiratory illnesses, (3) infections of respiratory and digestive tracts, (4) measles or chicken pox, and (5) prolonged illness. The healthy group was compared with each of the other groups for gain or loss in stature; weight; width of hips; girths of arm, leg, and chest; and thickness of skin and subcutaneous tissue. As in the earlier study, no statistically significant differences were obtained. The results from these studies should not be over-generalized. They are specific to young children from homes of fairly high socioeconomic level.

*Individual curves.* Growth trends for individual children covering time segments of 4 or more years, and falling mainly between the childhood ages of 4 and 11 years, have been studied for 9 different traits, namely: biparietal diameter,[30] bizygomatic diameter,[31] stem length,[6] upper limb length,[28] bi-iliocristal diameter,[33] lower limb length,[32] leg girth,[32] lower limb index,[32] and

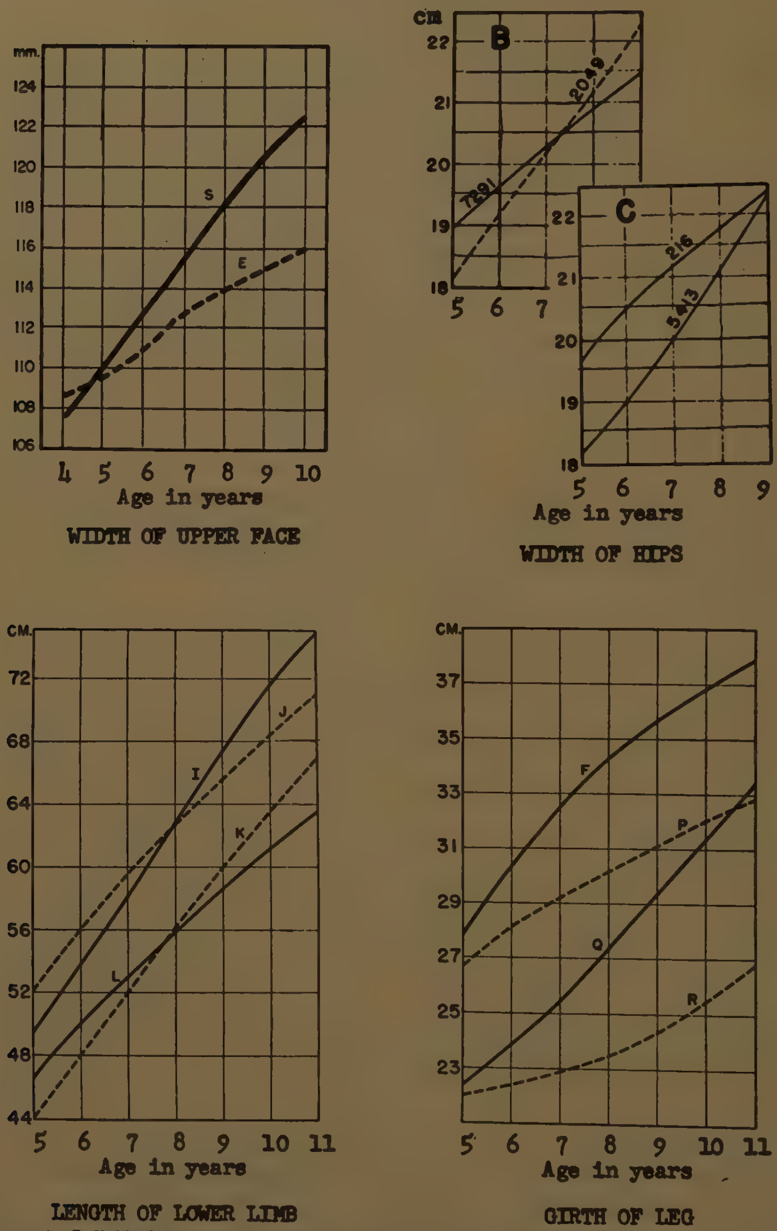
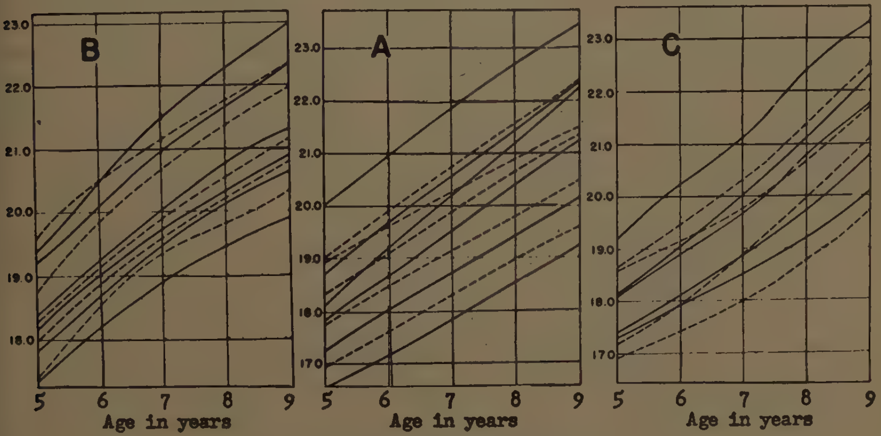


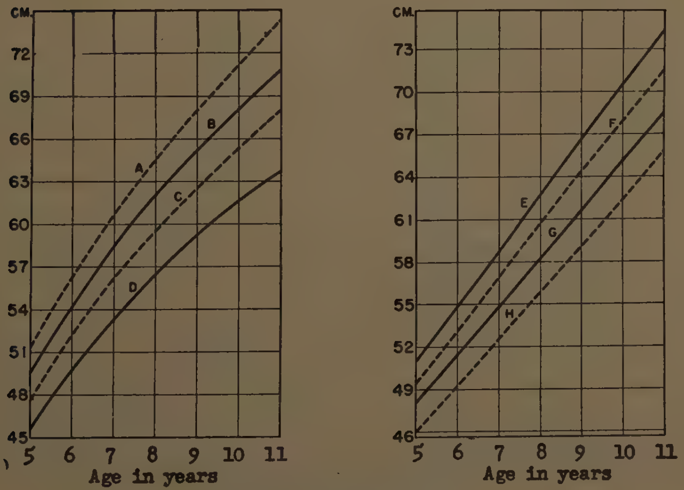
Figure 4. Individual differences in growth rate during childhood for four body dimensions. Reproduced from Meredith,[31] Meredith,[32] and Meredith and Carl.[33]

foot length.[27] Selected findings will be assembled on two topics: differences in the over-all slope of individual trends, and differences in curve pattern.

FIGURE 4 depicts individual differences in slope (*i.e.*, in growth rate) for bizygomatic diameter, bi-iliocristal diameter, lower limb length, and leg girth. For the other traits studied, differences will be illustrated by selecting two children alike at age 5 years and comparing their growth over the ensuing 4 years. Percentage increments over the age period 5 to 9 years were 1.4 and 4.2 for two girls having biparietal diameters of 14.4 cm. at 5 years, 14.2 and 17.0 for two boys having stem lengths of 61.7 cm. at 5 years, 21.8 and 25.9



BI-ILIOCRISTAL WIDTH OF HIPS



LENGTH OF LOWER LIMB

FIGURE 5. Patterns of individual growth for hip width over the age period 5 to 9 years (both sexes) and lower limb length over the age period 5 to 11 years (boys). Reproduced from Meredith[32] and Meredith and Carl.[33]

for two girls having upper limb lengths of 45.8 cm. at 5 years, 16.7 and 23.6 for two boys having foot lengths of 19.8 cm. at 5 years. For two boys with identical lower limb indices at 5 years (*i.e.*, leg girth 53.5 per cent of lower limb length), at age 9 years the one had an index higher by 2.9 per cent and the other an index lower by 10.9 per cent.

Differences in curve pattern have been studied to some extent for stem length,[6] upper limb length,[28] and foot length,[27] but principally for bi-iliocristal diameter,[33] lower limb length,[32] leg girth,[32] and the ratio of leg girth to lower limb length.[32] Shown in FIGURE 5 are examples of childhood patterns for bi-iliocristal diameter and lower limb length. It will be seen that absolute magnitude curves for lower limb length over the age span 5 to 11 years vary from rising rectilinear trends to rising trends concave to the base line. More than 80 per cent of the trends amassed for this dimension are negatively accelerated functions of age. The curves for bi-iliocristal diameter are rising trends differing in gross pattern from concavity, through linearity, to convexity. Individual trends for leg girth over the period 5 to 11 years have been found to vary through a similar range. The majority of curves for the ratio of leg girth to lower limb length follow a negatively accelerated course during the age period 5 to 11 years, *e.g.*, in a series of 70 curves, over 60 per cent were

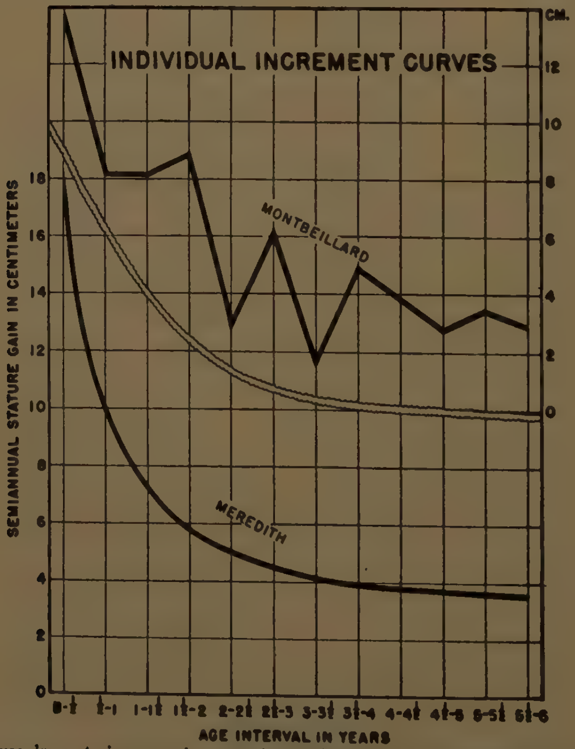


FIGURE 6. Curves drawn to increases in successive semiannual stature measurements on two boys. Data for upper curve from Scammon,[46] data for lower curve obtained at the writer's laboratory on T. K.

falling trends convex to the base line. Smaller numbers of these curves descend at a regular rate, or descend from 5 to 8 years to remain constant or ascend between 8 and 11 years.

To date, little has been done with respect to the analysis of individual increment curves. Work of this type will be reported soon; a major study is in process on increases in facial dimensions during successive semiannual periods. Graphic portrayal of gain (or loss) over consecutive age intervals is a particularly sensitive approach to the study of short-term departures from the general trend.[25] FIGURE 6 shows plots of semiannual stature increments for two boys over the period from birth to six years. The upper curve is from the earliest known seriatim study of human growth;[46] the lower curve represents a child in our program. Both curves have been drawn to unsmoothed values. The contrast provides striking re-emphasis of a central theme in this paper, to wit: in studying individual growth, the random error component must be satisfactorily reduced before substantial findings can be secured on the occurrence or nonoccurrence of short-term morphologic undulations.

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# RELATIVE GROWTH OF THE HUMAN FETAL SKELETON, CRANIAL AND POSTCRANIAL

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*Introduction.* The growth of the human fetus is characterized by great changes in relative proportions that occur simultaneously with absolute increases in size. Such proportional changes are not haphazard. They occur in an orderly, progressive sequence. These quantitative changes are capable of simplified expression.

In the field of normal human growth and development, the literature contains a great many excellent morphological studies of the tissues and organs undergoing these proportional changes. These data, however, remain essentially static and particulate, rather like a series of still photographs. If we wish to view the subject of human growth from a more dynamic aspect, we find that a different, but not necessarily better, methodology is required.

It is quite proper to concern ourselves with the *relationships* existing between the individual events of growth rather than with their detailed description. The introduction of allometric growth concepts into this field has proved useful. Such a quantitative technique should fulfill two requirements. First, the results of such an analysis should furnish a simplified statement concerning the growth processes. Secondly, the results should aid in the correlation of the descriptive growth data of the individual structures and tissues.

*Application to bone growth.* The application of differential growth analysis to the study of human growth has been rare (Cawley *et al.*, 1949; Jaso, 1951; Forbes, 1952). Specifically, the use of this technique in the study of human skeletal ontogenesis has been subjected to serious methodological doubt. Recently, Reeve and Huxley (1945) stated that bone tissue was not amenable to such analysis, since its mode of growth was not multiplicative in nature. This statement arose, apparently, from semantic misunderstanding. These authors correctly argue that bone does not grow interstitially, but by the processes of surface accretion and resorption. Bone morphology then, in this sense, is simply the result of additive growth. The term *accretion* unfortunately held their attention. In this same article, however, the authors do point out that in many subhuman forms, relative growth analysis was quite useful in explaining changes of osseous proportions. This wavering position suggested the need for further study of the problem.

A new viewpoint is possible that is consistent with the theoretical postulates of relative growth analysis. The osteogenic tissues themselves undergo multiplicative growth. The bone tissue that subsequently forms may be regarded as the visible resultant of this antecedent soft-tissue growth. In measuring bone, then, we do not measure *what* grows, only the *result* of that growth, and that at second hand.

Preliminary studies were made of the postnatal growth of certain human mandibular segments. The growth of these segments was found capable of expression by the allometric growth formula (Moss, 1954). Subsequent to this publication, the data of Inghram (1932), dealing with the prenatal stages of this growth were analyzed. The prenatal data proved to fit the regression line derived from the postnatal material.

It was decided to extend this study to the growth of the entire human fetal skeleton, cranial as well as postcranial. Human *fetal* skeletal growth was selected, for it is characterized by great changes in proportions that accompany increases in absolute size.

*Materials and methods.* A series of 119 alizarinated human fetuses, 14 mm. to 175 mm. CR (55 to 133 days of menstrual age) were available to us. The lengths of all of the long bones, as well as of the clavicle and sixth rib were measured. The methods used and the absolute values obtained are published elsewhere (Moss, Noback, and Robertson, 1955a). In addition, the several dimensions of certain cranial bones were also measured. The specific methods of this study, together with the absolute data, are presented elsewhere (Moss, 1955; Moss, Noback, and Robertson, 1955a and 1955b).

The differential growth relationships between all of these dimensions were plotted. In addition, each of these dimensions was plotted against the log of crown-rump length and against the log of time (Levy, 1952).

The results of this analysis showed that human fetal skeletal growth was

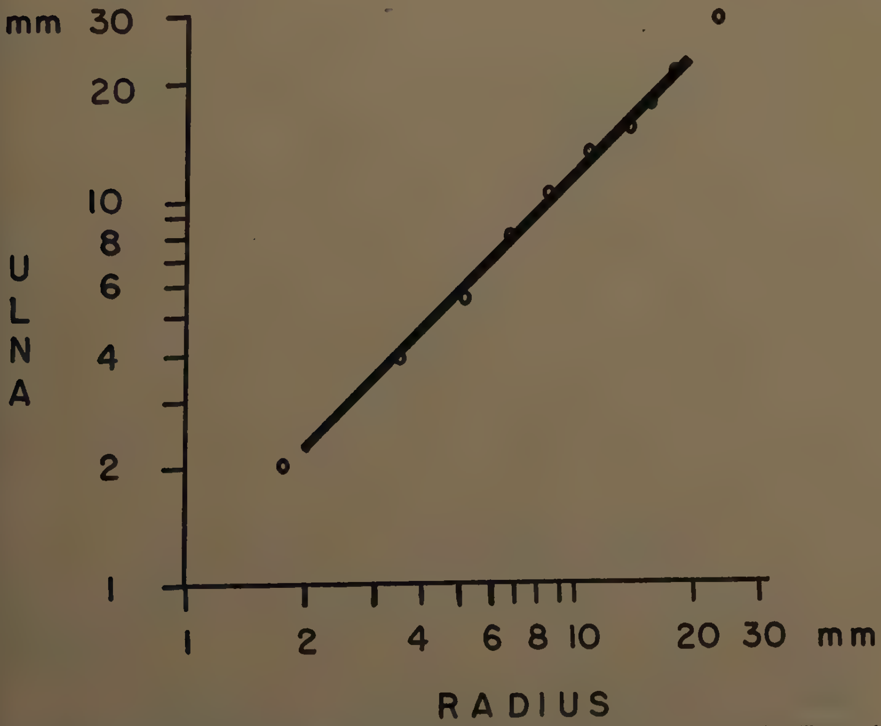

FIGURE 1. The linear relationship between the specific growth rates of the two osseous dimensions illustrated here is characteristic of any combination of postcranial skeletal dimensions.

capable of a simplified quantitative expression by the allometric growth formula. It was shown further that a critical developmental horizon existed for all of the skeletal system, at the end of the first trimester. This horizon was characterized by a change in the value of the growth ratio ($k$) in the formula $y = bx^k$. This critical period was found to be correlated with a great many morphological events in the neighboring tissues and structures of the fetal body.

*Postcranial skeleton.* The ratio of the specific growth rates of any combination of bone lengths remained constant throughout the period of growth covered by the study (FIGURE 1). It was easy to ascertain that the constituent bones of both distal limb segments grew relatively faster than those of their respective proximal segments. Further, each segment of the lower extremity grew relatively faster than its corresponding segment in the upper extremity.

When each of these osseous dimensions was plotted against the log of crown-rump length (FIGURE 2) or against the log of time (FIGURE 3) a change in linear slope, or interphase, was noted. The values of these two parameters was essentially identical (80 to 89 mm. crown-rump length; 89 days, menstrual age) for each of the osseous dimensions.

It was obvious that since the interosseous ratios remained constant before and after the interphases, some common factor intervened simultaneously in

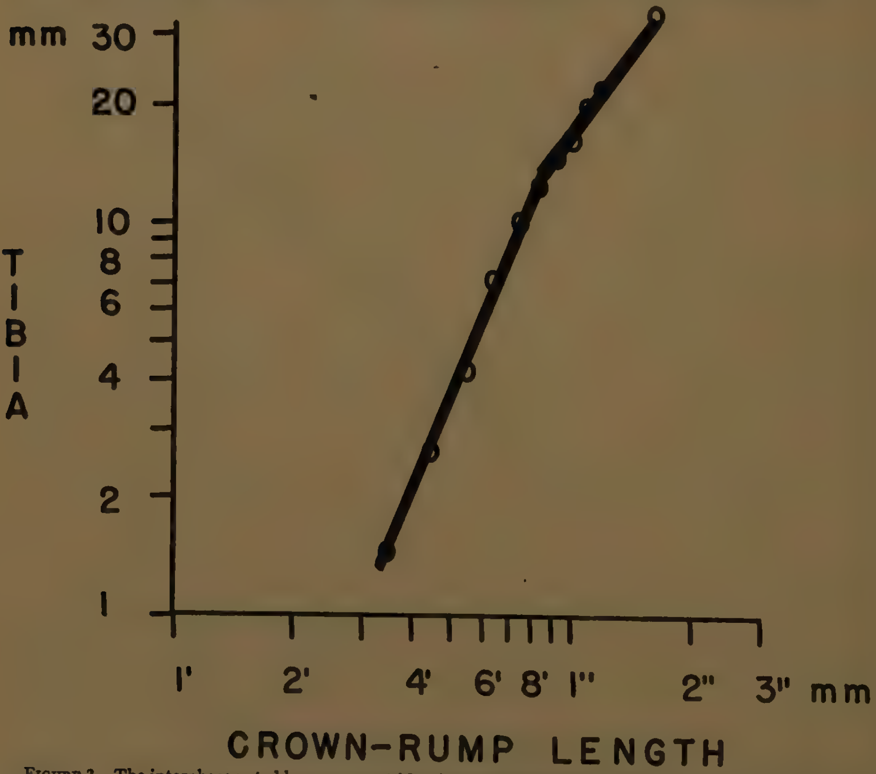

FIGURE 2. The interphase noted here occurs at identical values (80–89 mm. crown-rump length) for all post-cranial bones.

the growth of all of the postcranial skeletal bones. The observation of these common critical developmental horizons was of great value. They clearly indicated the stages of fetal development in which we might confidently expect to find correlated growth changes in the adjacent tissues and structures. This expectation was realized.

In brief, the occurence of the interphases was found to be correlated with a most profound alteration in the mode of long-bone growth. The percentage of gross body segment, as well as the percentage of skeletal blastemal length which the osseous shaft occupied, increased rapidly until the stage of the interphase, and thereafter was almost constant. In addition, endochondral ossification began at the period of the interphase. The epiphysial cartilage plate now assumed the structure characteristic of the region in the growing child. The bony diaphysis began to increase in thickness, and the histological structure of the bone became more mature. Additional details will be found in our cited reference (Moss, Noback, and Robertson, 1955a).

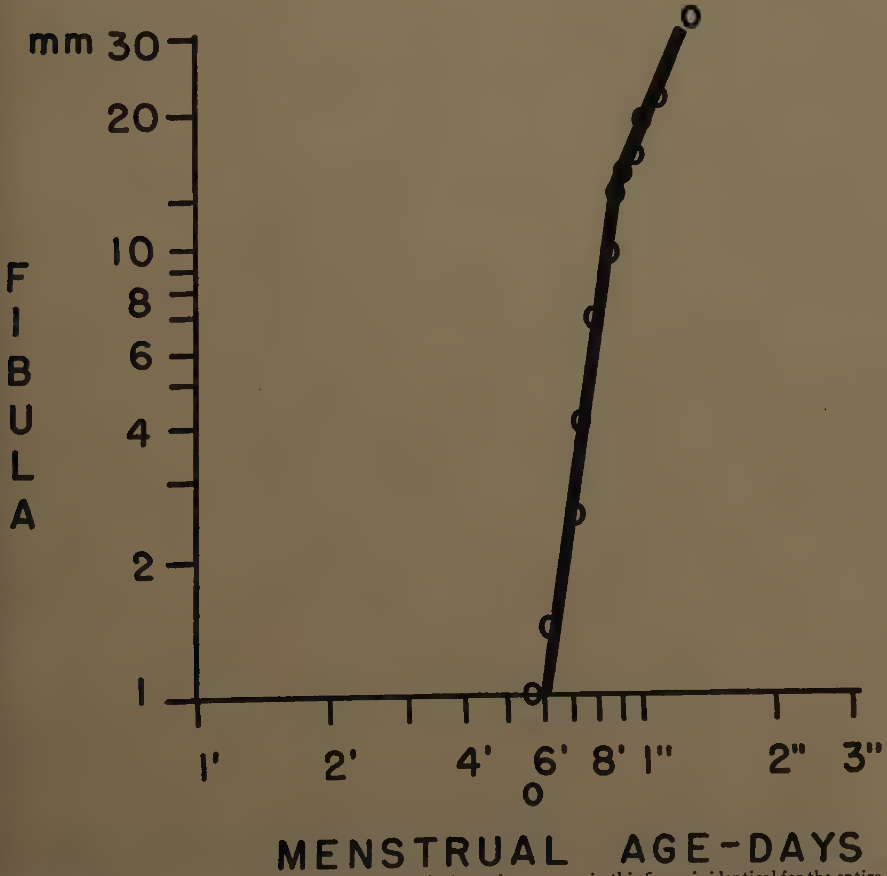

Figure 3. The menstrual age (89 days) at which the interphase occurs in this figure is identical for the entire postcranial skeleton.

*Cranial skeleton.* The results of the differential growth analysis of the cranial skeleton did not differ essentially from that of the postcranial skeleton. Exceptional growth characteristics were exhibited by only one dimension of one bone, the width of the cartilagenous portion of the occipital bone squama. This, in itself, proved most instructive and will be referred to below.

As in the postcranial skeleton, any pair of dimensions, intraosseous or interosseous, showed a constant ratio between the two specific growth rates. Further, any cranial dimension showed a constant ratio when plotted against any postcranial dimension. When any of these dimensions were plotted against the log of crown-rump length (FIGURE 4) or against the log of time (FIGURE 5), characteristic interphases were again noted. These changes in linear slope occured at the same values for these two parameters, as was the case in the postcranial skeletal growth analysis.

The stage at which these interphases occured was further characterized by several other correlated events. The cerebral hemispheres, at this time, achieved a proportional representation in the brain as a whole that was essentially mature. At the same stage, and as a result of this neural growth, the tentorium cerebelli attained a definitively adult position in respect to the over-

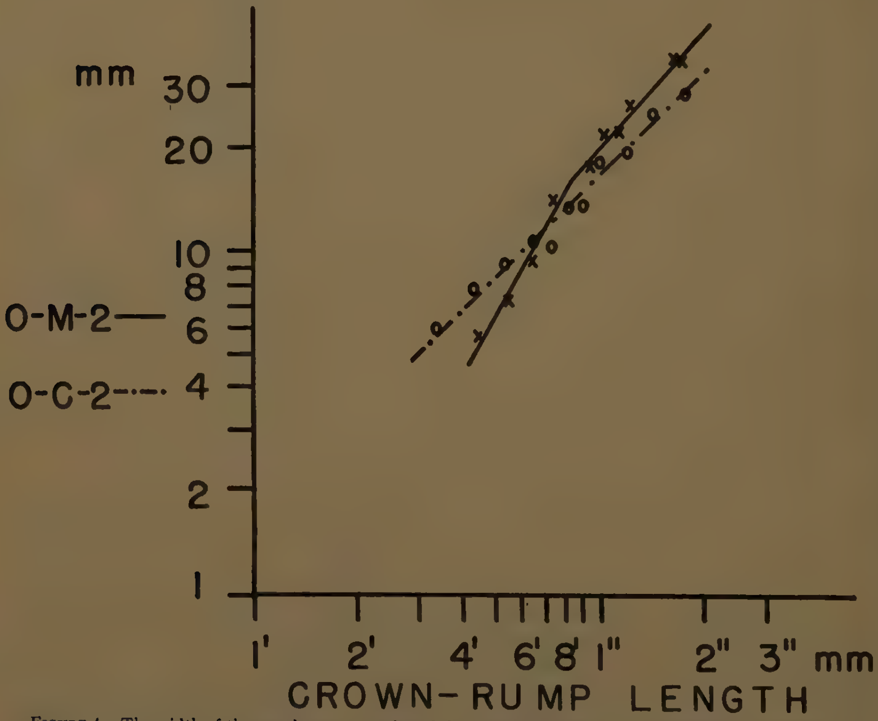

FIGURE 4. The width of the membranous portion of the occipital squama (O-M-2) shows an interphase at an identical value as that observed with all cranial dimensions. This value is identical (80 to 89 mm.) with that for the postcranial skeleton. The only cranial dimension which did not show an interphase was the width of the cartilagenous portion of the occipital squama (O-C-2).

lying calvaria. The cranial bones themselves achieved their definitive position within the osseo-membranous neural capsule. Microscopically, the bones began to show certain histological alterations in their structure symptomatic of their maturation. A more detailed report will be presented elsewhere (Moss, 1955; Moss, Noback, and Robertson, 1955b).

*Interrelation of brain and skull growth.* We have noted some aspects of the quantitative relationships existing between the growth of the skull and the growth of the brain. The inference, obviously, was that the growth of both components was closely correlated and coordinated. The analysis of our one exceptional cranial dimension made this coordination even more apparent. We noted that the growth in width of the cartilagenous portion of the occipital bone squama was exceptional. Reference to FIGURES 4 and 5 clearly shows that this dimension did not show an interphase when plotted against the log of crown-rump length or against the log of time. Moreover, this dimension, alone, showed an interphase when plotted against either postcranial dimensions (FIGURE 6) or cranial dimensions (FIGURE 7). These phenomena were found to be well correlated with the growth in width of the cerebellar hemispheres. This brain dimension does not begin its growth until the end of third fetal month. It showed exceptional growth characteristics in the differential

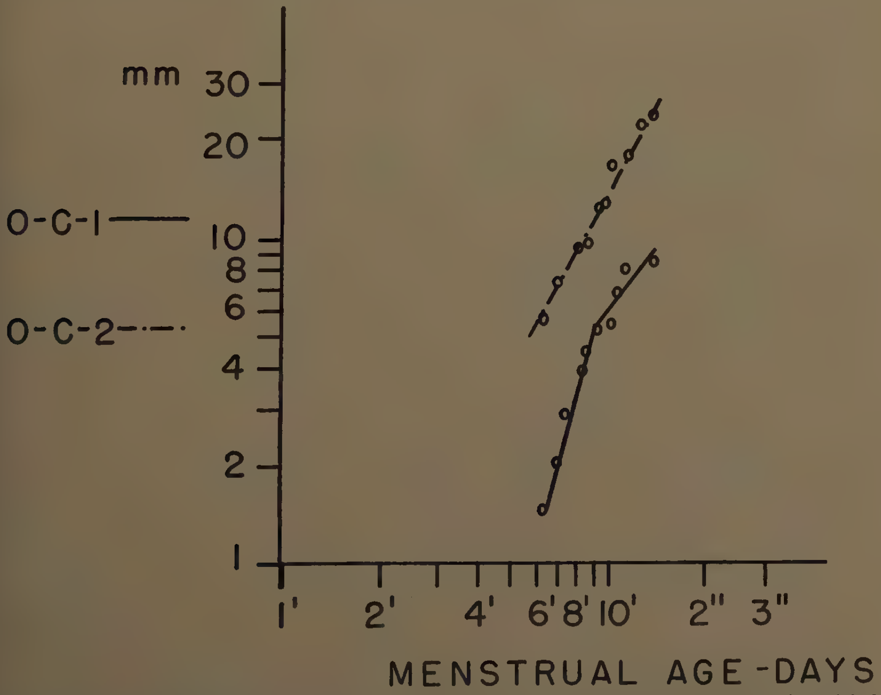

FIGURE 5. All cranial dimensions, as typified by O-C-1 (the height of the cartilagenous portion of the occipital squama) showed an interphase against time, at identical ages (89 days) as the postcranial skeleton. Note that O-C-2 did not show this interphase.

growth analysis of the human fetal brain (Noback, 1955; Noback and Moss, unpublished). This portion of the calvaria, therefore, had a growth behavior that was closely interrelated with the growth of its underlying brain segment.

The growth of the components of the skull base were not included in this study. It has been shown, however, that the growth of certain selected dimensions of the human fetal skull base were capable of allometric analysis (Pankow, 1951; Kummer, 1952).

In summary, the growth of the entire human fetal skeleton may be analysed by differential growth techniques. By such methods, quantitative statements may be made concerning relationships existing between the growth of any given pair of osseous dimensions. As a result of this, the changes in bodily proportionality during fetal development find simplified quantitative expression, in terms of the computed values for the growth coefficient (*k*). This fulfilled the first of the two requirements we originally postulated. The second requirement, aiding in the correlation of descriptive growth data, seemed to have been well met also. It proved quite feasible for us to search the literature of hu-

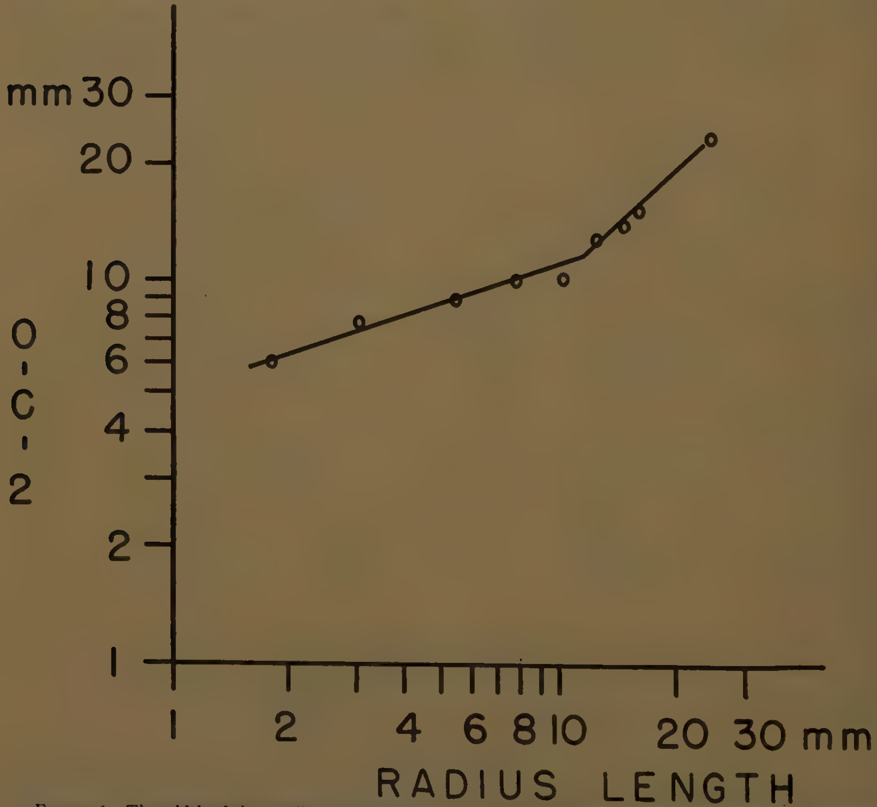

FIGURE 6. The width of the cartilagenous portion of the occipital squama shows an interphase in the ratio between its specific growth rate and that of the radius. All other measured cranial dimensions show no such interphase in their growth relative to postcranial dimensions.

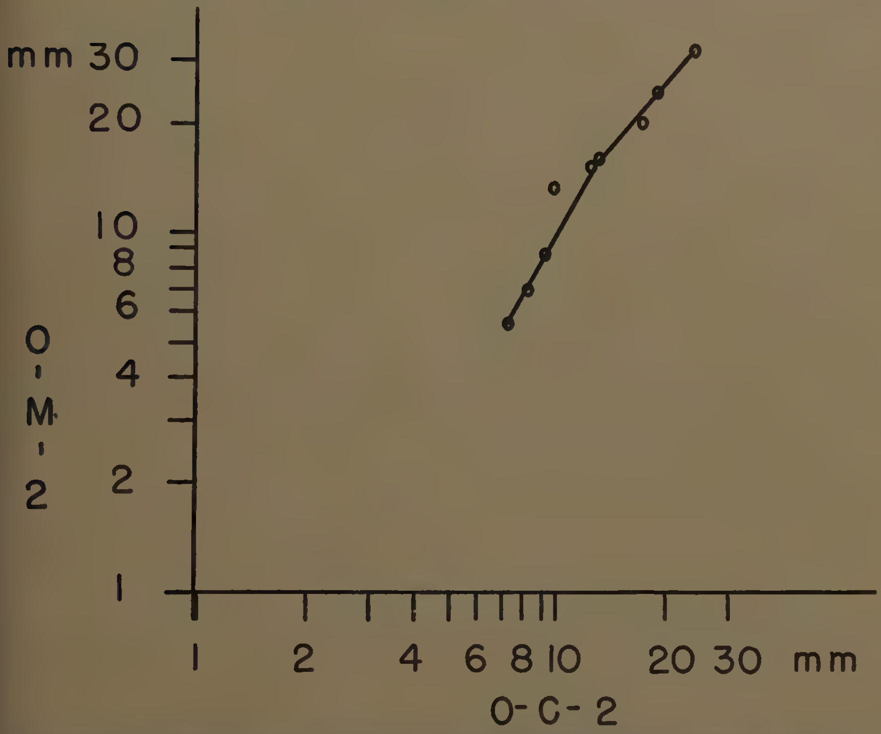

Figure 7. This figure demonstrates, as above, the singular behavior of this cartilagenous dimension. In this case, a cranial dimension is selected. This dimension grows relatively faster than any cranial or postcranial dimension in order to provide space for the rapidly growing cerebellar hemispheres.

man embryology, dealing with the periods of the observed interphase, and to make more comprehensible the various descriptive data recorded there. All of these diverse observations now fell into order, giving us a more dynamic picture of human skeletal ontogenesis. It must be noted, on the other hand, that this empiric method still does not give us any understanding of the *nature* of the growth processes.

One final conclusion was drawn from our results. The growth of the human fetal skeletal system was shown to be a unitary event. That is, despite the dual origin of the individual bones, either membranous or endochondral, a single pattern of growth applied. This unity was not affected by changes in the mode of bone formation, nor by the histological changes in the bones themselves. The occurance of critical developmental horizons at essentially similar values of crown-rump length and of time emphasized this point.

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# APPLICATIONS OF PATTERN ANALYSIS TO ANTHROPOMETRIC DATA*

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Traditionally, anthropometric data have been considered measurement by measurement, or as pairs of measurements. This was true in Camper's time, at the very beginnings of anthropometry and, to a large extent, it is true today. Statistical techniques, of course, have added greatly to the utility of the measurements. We are able to state the probability that a given difference could or could not have been obtained by chance. Mathematical techniques have been expanded so that we are able to calculate the exact transformation that makes two variables assume a useful straight-line relationship. Factor analysis has made possible the discovery of "vectors" or directions not easily uncovered by simple correlations alone. Still, anthropometric data are most often analyzed measurement by measurement, or as pairs of measurements, leaving analysis of the data as a whole to some future date.

Well back in the present century, the need for more encompassing methods of analysis was realized. Population *A* averaged bigger than population *B*. Were the metrical differences between these two populations all due to the simple difference in size, or were there residual differences due to sampling from separate gene pools? Many fossil men had teeth appreciably larger than those found in contemporary populations. Were such paleanthropic dentitions simply *larger*, or did they differ qualitatively from neanthropic dentitions as well? That differences or similarities could be expressed in terms of patterns was, of course, evident, but the problem of how to represent the patterns and how to analyze them was not solved. And, as we know, additive coefficients of similarity did not prove to be the answer to pattern comparison and pattern analysis of anthropometric data.

But it would be wrong to give the impression that patterning and pattern analysis have been entirely neglected in anthropometry. The little stick men that Stratz and others have employed right up to the present constitute attempts at graphical representation of patterned differences. The metatarsal "patterns" of Morton and others, like the digital formulas, are patterns in every sense. Hellman's famous "wiggles" that plotted the millimeter deviations of orthodontic patients in reference to the standard deviation limits of occlusally-normal controls, stand in the phylogenetic line of anthropometric pattern analysis[1] (see FIGURE 1). Yet it must be admitted that patterning and the analysis of patterning as yet holds no major place in the anthropometric armamentarium, and it is difficult to recall a single paper devoted to pattern analysis in the anthropometric literature of the past few decades.

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* The author acknowledges the assistance of Richard W. Young, Georgia R. Greaney, and Ruth V. Harper. The advice of Doctor John I. Lacey and, in particular, his suggestions on profile analysis have proved especially valuable.

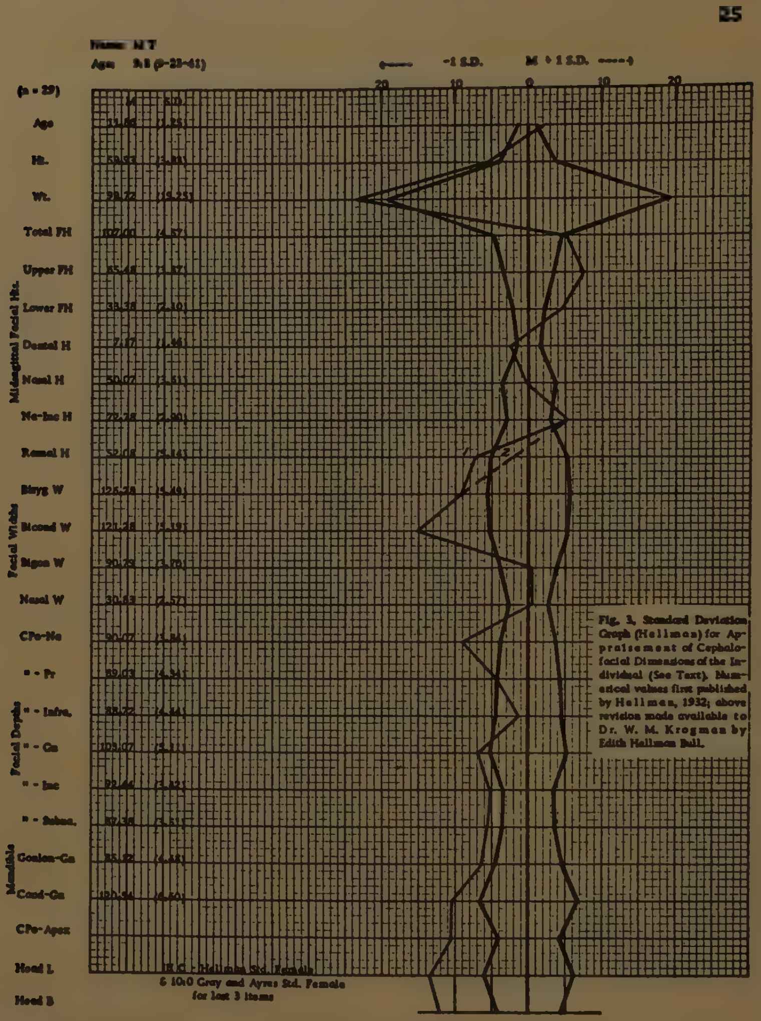

FIGURE 1. The Hellman "wiggle," reprinted from Snodgrasse.[2] In this early attempt at pattern analysis, the inclusion of both uncorrelated and highly correlated variables, and the form of presentation (in which variability is not equalized) make difficult the appraisal of any specific pattern.

## *Pattern Analysis in Psychometry*

Patterning, however, has come to be of major interest in the fields of psychology, education, and personnel placement. For it has long been noted that "patterns" or configurations formed by the scores of individual items in a test battery, or components of a single test, are far more characteristic of the individual and often more useful for diagnostic purposes than a single additive weighted value.

In the personnel field, it is a commonplace that "individuals successful in a given occupation tend to manifest patterns of ability quite distinct from the patterns exhibited by persons in other occupations and in the general population."[3] Personality patterns, *i.e.*, the configurations of score values in a multiscore test, also reveal individual differences, many of them of practical predictive value. Probably, without thought of patterning in the formal sense, those of us responsible for the selection of graduate students are often influenced by the pattern of grades received. We are more likely to welcome a four-B, one-A, and one-C student to graduate work in biostatistics if his A is in mathematics and his C in music, than vice versa.

Yet for the most part, and because of operational necessities, the mathematical analysis and comparison of ability patterns has been of less interest in the personnel field than their visual appraisal (for a review, see Traube's article).[4] But in psychology, pattern analysis has gained very considerable popularity. The necessary prerequisite to many types of pattern analysis, namely, putting different tests on a comparable basis through the use of $Z$ scores or normalized $T$ scores, is practically a routine activity in psychometrics.

Most, in fact nearly all, of the attempts at pattern analysis and at devising suitable techniques for pattern matching are to be found in the psychological literature. Techniques have been developed for (1) pattern representation; (2) pattern matching; and (3) pattern prediction. Some of the techniques of analysis, sufficient to handle two-value or three-value pattern profiles do not concern us here.[5] Some of the problems, involving levels, again may be ignored for our immediate purposes. But the very considerable investment of effort and thought on the part of psychologists and psychometricists yields dividends in terms of our own often simpler problems. We are most fortunate that our units of measurement are agreed-upon, equal-interval, and constant. Therefore, anthropometric data are perhaps more readily represented in pattern form, and pattern congruences more easily compared than is usually true for the raw data with which psychometricians work. Moreover, the recurrent and bothersome problem in psychometrics, namely, whether patterning exists or not (for any specific case) is rarely a major problem to us. We are fortunate in being able to select anthropometric measurements where patterning is demonstrable and clear.

### *The Absolute Pattern*

The absolute pattern, as it will be termed here, consists of the absolute or raw-score values for $n$ measurements (whether correlated or not) plotted on a suitable coordinate system. This absolute pattern, which is no more than a graphical representation of the metrical data, immediately summarizes in visual form the patterned characteristics of the individual or the group (when mean data are used). It thus makes available the "Gestalt" and facilitates comparing (a) individuals to individuals; (b) groups to groups; and (c) individuals to groups. In utilizing such absolute patterns, attention may be paid to levels. Thus the fat patterns of obese and lean men may be compared, or the tooth patterns of Australian aborigines and Finnish Lapps may be contrasted. Pattern configuration can be noted: subcutaneous fat patterns for individuals of the same sex form a family of profiles. And, in particular, pattern *reversals* can be observed.

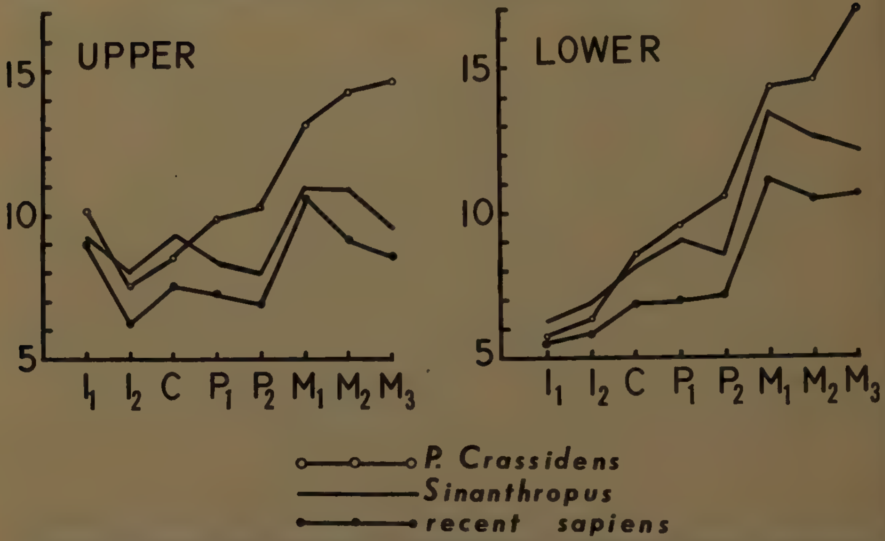

FIGURE 2. Tooth-size profile patterns for an Australopithecine (*Paranthropus crassidens*), *Sinanthropus*, and recent man, redrawn from Von Koenigswald.[6] The profile similarity between *Sinanthropus* and modern man is evident, as is the greater divergence of the Australopithecine tooth-size profile.

By way of example, the tooth-size measurements of various fossil forms and recent hominids when compared measurement by measurement, show that such fossils as the various Australopithecines, *Sinanthropus* and *Pithecanthropus*, all had larger teeth than recent man. Such measurement-by-measurement comparisons have led Robinson, among others, to postulate an Australopithecine ancestor for the megadonts of Southeast Asia. But when the pattern profiles involving the same measurements are compared, it is immediately evident that the *Sinanthropus* dentition is patternwise similar to modern man, while the pattern profile of *Paranthropus crassidens* differs from both *Sinanthropus* and "recent man" (FIGURE 2). In terms of the tooth-size pattern, here redrawn from Von Koenigswald,[6] one might hesitate to derive the Chinese subspecies of *Homo erectus* from an Australopithcine ancestor, but hesitate less to derive contemporary *Homo sapiens* from *Homo erectus* of Southeast Asia.

Or, to deal with softer tissues than enamel and dentine, one may consider absolute fat patterns in adults; that is, the profile patterns formed by plotting 9 or 10 different subcutaneous fat thicknesses on a suitable coordinate graph. As shown in FIGURE 3, the absolute fat patterns of men fat and lean, though differing in detail, fall into a family of profiles. And the same is true of women, who are (as shown) generally fatter. Thus, a fat woman merely exaggerates the fat profile pattern of a thin woman, rather than possessing a different fat profile pattern.

Yet, when we contrast the fat profile patterns of a fat man and a fat woman (FIGURE 4) both similarities and sexual divergences are seen. In three arm fat thicknesses, and in iliac fat, the two individuals pictured agree nearly perfectly. But in trochanteric fat, and in leg fat thicknesses, the fat woman grossly

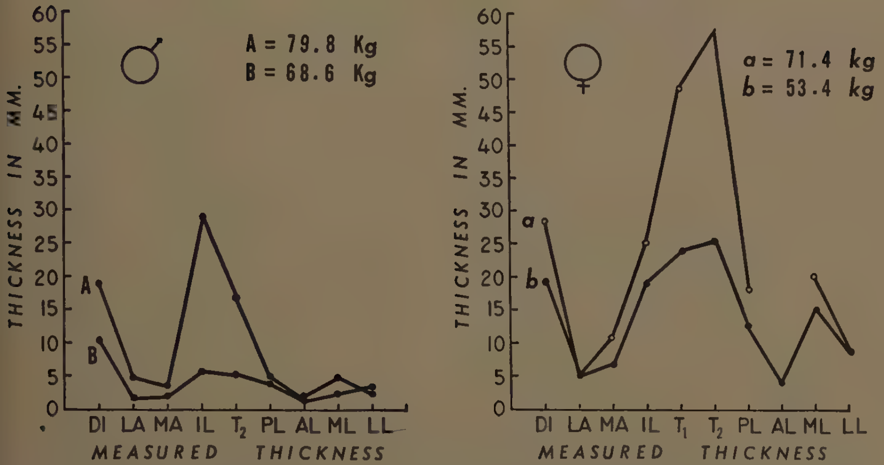

FIGURE 3. Comparison of absolute fat patterns of fat and lean men (left) and fat and lean women (right). For each sex, there is a family of profiles, while the sex divergence is evident as a difference in levels. For an explanation of the measured thicknesses (DI, MA, LA, *etc.*) refer to the article by Garn.[10]

exceeds the comparably fat man. Thus simple inspection of the absolute fat patterns here pictured reveals how little sexual dimorphism there is (except in levels) above the waist, and how great the extent of dimorphism is below.

But FIGURES 3 and 4 also reveal the major failing of absolute patterns, namely that individual differences are not easily discerned. Men, as a group, have a characteristic fat pattern: a given male is either more so or less so, but only the pathological male would depart markedly from the group absolute patterns (the same is probably true of the female, but here our data analysis is not yet complete). But what of the individual who is a little fatter on hip or arm, a little leaner on thigh or leg, than might be expected for his over-all fat ranking? To investigate such individual differences, we must depart from the absolute pattern, to the relative ($T$-score or $Z$-score) pattern. This expedient, which compares an individual to the norm or "zero" pattern for the group, also corrects for patterned differences due *solely* to (1) differences in size; or (2) differences in the amount of a particular tissue present. Relative patterns, then, are the substance of the next section.

### *The Relative Pattern**

The "relative" pattern is represented in a fashion similar to the absolute pattern, by plotting the values for $n$ measurements on as many vertical axes, on a suitable coordinate grid. The difference is that, instead of the absolute values (*i.e.* raw scores), the ordinate is marked off in $Z$-score or $T$-score units instead. Thus for each measurement, the individual value is expressed *relative* to the group. Each axis has the same mean (0 in $Z$ scores, 50 in $T$ scores), and the standard deviation (S.D.) is the same for each axis (1 in $Z$ scores, 10 in $T$ scores). For a hypothetical individual exactly 1 S.D. above the mean in $n$ measurements, all values would lie at $T = 60$ or $Z = +1$ throughout. The relative pattern profile would thus be a straight line, indicating a zero relative pattern for this individual.

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* The term "relative pattern" emphasizes the fact that $Z$-score or $T$-score patterns are relative to the group mean. An individual exactly at the mean, in all items comprising the pattern, or at a constant distance above or below the mean would thus have a null or "zero" relative pattern.

Without going into the advantages of $T$ scores over $Z$ scores, except to note that normalized $T$ scores correct for the skewness nearly always present, both $Z$- and $T$-score profiles make it possible to represent an individual in relation to the normative pattern for the group. As applied to the dental measurements previously pictured, but using Moorrees' norms as a baseline, the relative or $Z$-score tooth patterns for *Sinanthropus* and *Paranthropus* both differ from modern

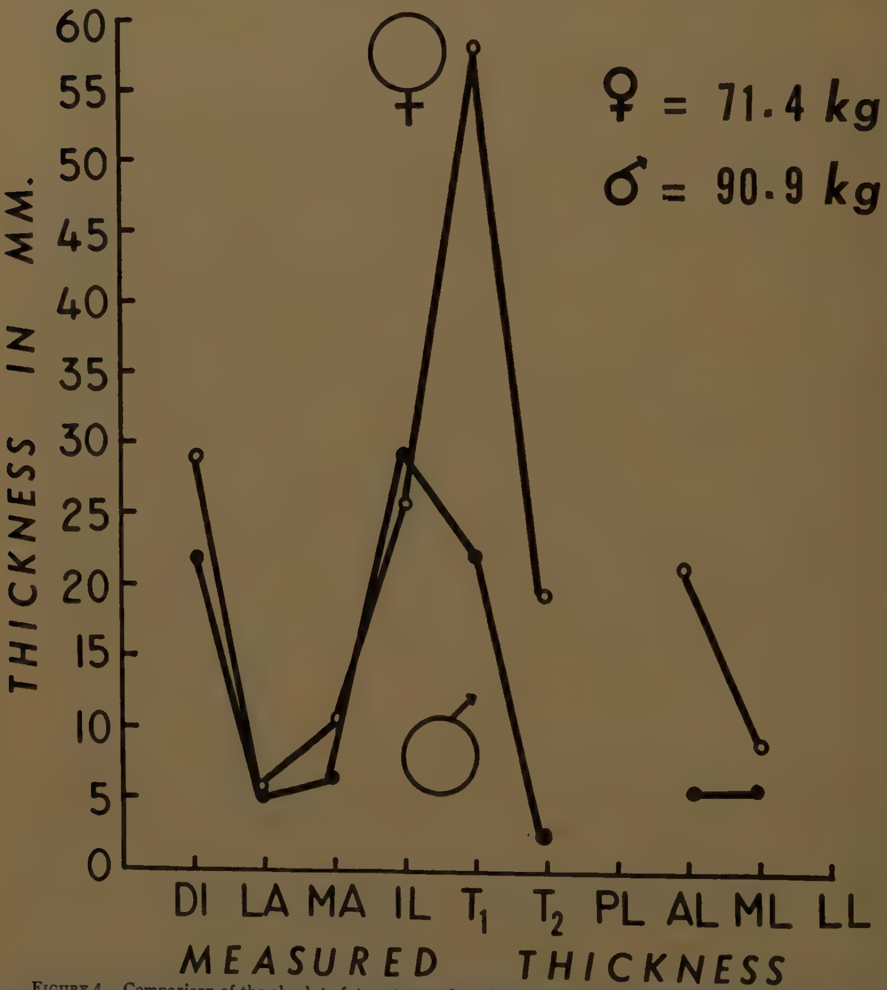

FIGURE 4. Comparison of the absolute fat patterns of an obese woman and a moderately obese man. While the two are closely congruent in deltoid insertion fat (IL), through iliac fat (I) there is a great pattern divergence in trochanteric fat ($T_2$) and the leg thicknesses (AL, ML, LL).

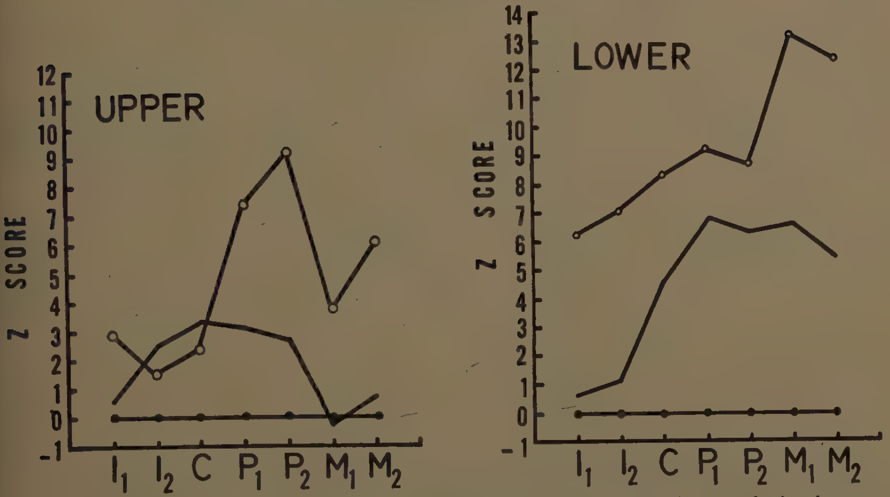

FIGURE 5. Relative (or *Z*-score) tooth-size patterns, for *Paranthropus* and *Sinanthropus* and using the norms of C.F.A. Moorrees as a baseline (with permission). Note that while the Australopithecine dentition diverges most from modern man, the mandibular and maxillary tooth-size patterns differ to different extents.

Americans, but the Swartkrans pattern differs the most (FIGURE 5). When the relative fat patterns of individuals are plotted, two facts of interest emerge. First, many and perhaps the majority of men approach a "zero" relative fat pattern. That is, their fat is distributed about as we should expect for their amount of fat. Second, some men have distinctly aberrant and unique relative fat patterns. They have unexpectedly more fat, or less fat, on some part of the body, than would be anticipated for them (FIGURE 6). Here, one still-unpub-

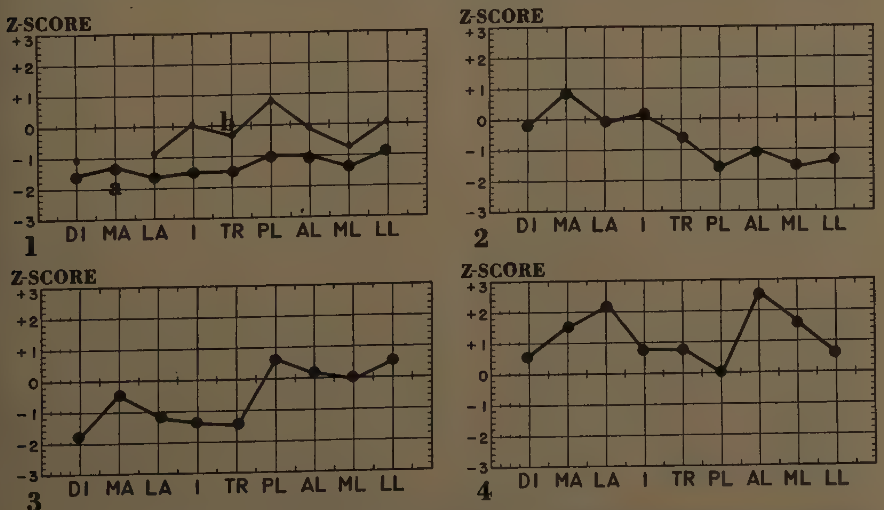

FIGURE 6. Representative adult male relative fat patterns. (1) A 39-year-old individual approximating a null or "zero" relative fat pattern at *68.6* kg. (a) and, 1.5 years later, at *75.9* kg. (b). (2), (3), and (4) Examples of "upper extremity," "lower-extremity," and "peripheral" relative fat patterns.

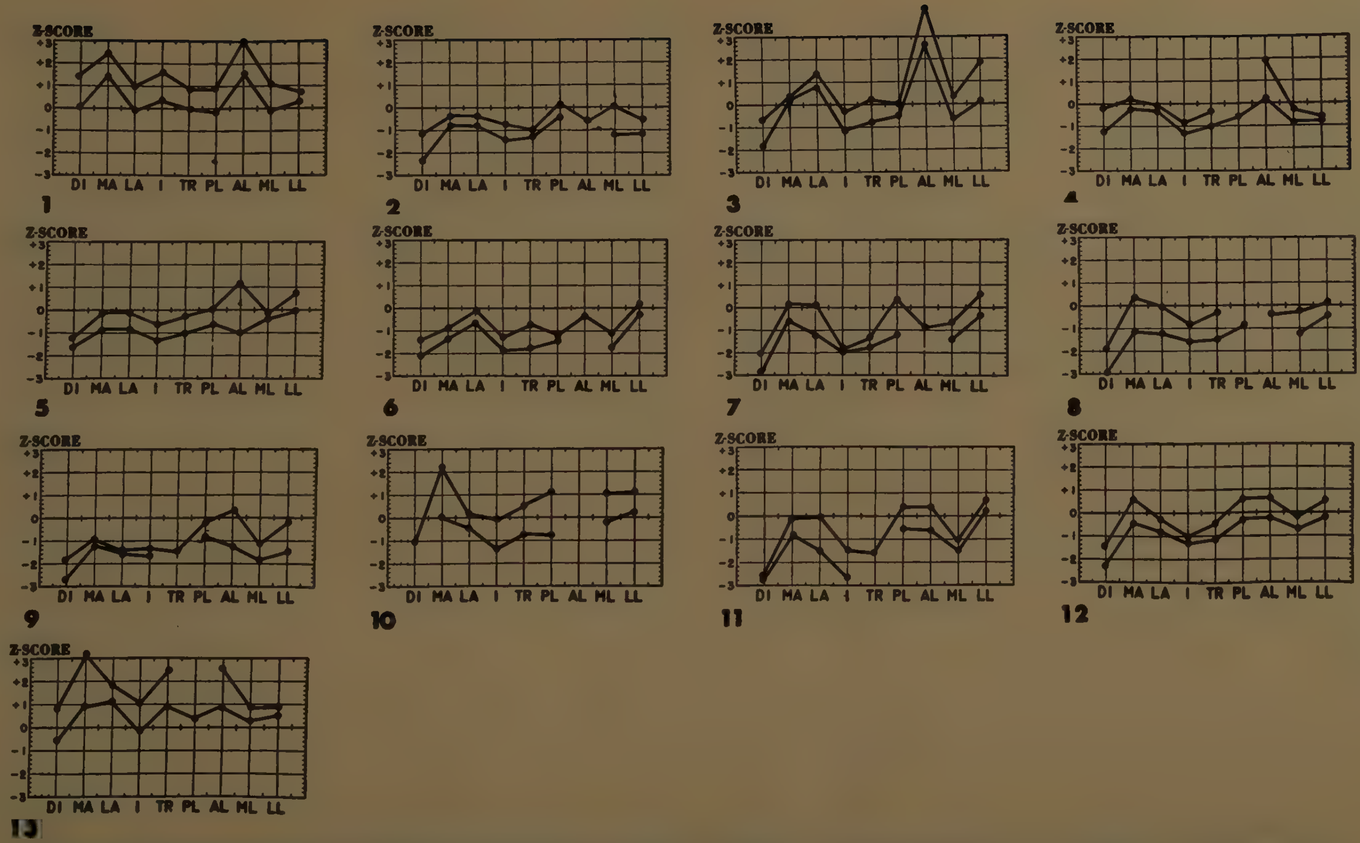

FIGURE 7. Relative fat patterns of 13 young males before and after a period of food restriction. Despite a generalized fat loss, as shown by the downward shift in levels, there was a striking tendency for each relative fat pattern to hold configuration. In each case, the lower profile is the "after" pattern.

lished comparison of the relative fat patterns in a set of monozygotic male triplets may be in order. These triplets (now aged 24 years) live apart. Two are married and one is not. In amount of fat they are vastly different. With over two sigmas between two of them in the amount of fat, one could hardly argue that subcutaneous fat is genetically determined. Yet the relative fat patterns of all three are strikingly similar, thus suggesting that the fat pattern, rather than the amount of fat, is subject to genic mediation.

These relative fat patterns, it may be added, appear to have some permanence in time, even though fat is gained or lost. For example, the relative fat patterns of 13 young men who incurred a 60,000-calorie debt did not change markedly.* Their "before" and "after" relative fat patterns, as shown in FIGURE 7, closely resembled each other with a surprising degree of pattern congruence. Thus individual No. 1 in FIGURE 7, who lost 14 kg. and whose *absolute* fat pattern changed greatly, maintained his *relative* fat pattern to a degree only slightly short of perfection. Naturally, there is as yet no proof that such relative fat patterns are completely permanent, or that comparable results would have been obtained if the caloric debt had been spread over a longer time. Yet the results do indicate that relative patterns may be fixed to a degree that absolute patterns are not.

The relative or $Z$-score pattern takes account of the differing variability of the component measures. As applied to fat, sigma for one area (anterior leg) is less than 1 mm.; for another area (trochanter), it is 7 mm. Other anthropometric measurements show even greater differences in variability. A thick hair may be 20 $\mu$ above the average, while a tall man may be 10 cm. over the mean: both may hold equal levels when plotted in terms of $Z$ or $T$ scores. Thus the well-nourished American of Tuscan descent, admittedly longer in limb than his European cousin, may turn out to be identical in relative pattern since $Z$s and $T$s correct for differential variability in the different body segments. Relative patterns may turn out to be the answer to comparing populations $A$ and $B$ mentioned in the introduction and may thus rescue racial anthropometry from its present position of discard.

## *Pattern Matching*

With relative patterns, even more than with absolute patterns, techniques for pattern matching are needed. Whether working with twins, siblings, or the before-and-after patterns of the same individual, the problem is often whether, and to what extent, two patterns are closely congruent.

Here visual inspection may be satisfactory. If two patterns involving the same number of items are plotted on the same system of coordinates, inspection will show whether they are identical, similar, or totally unlike. As used by the United States Employment Service, visual inspection, aided by pattern templates, helps to determine the ability pattern of an applicant and hence his most likely area for employment. Visual inspection seems to be the only technique that affords comparison of both level and configuration while indicating the

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* This work was carried on at the Laboratory of Physiological Hygiene, University of Minnesota, Minneapolis, Minn., in conjunction with Doctor Josef Brožek, and was supported under contract *DA-44-109-gm-1526*. The opinions stated are not necessarily those of the United States Department of Defense.

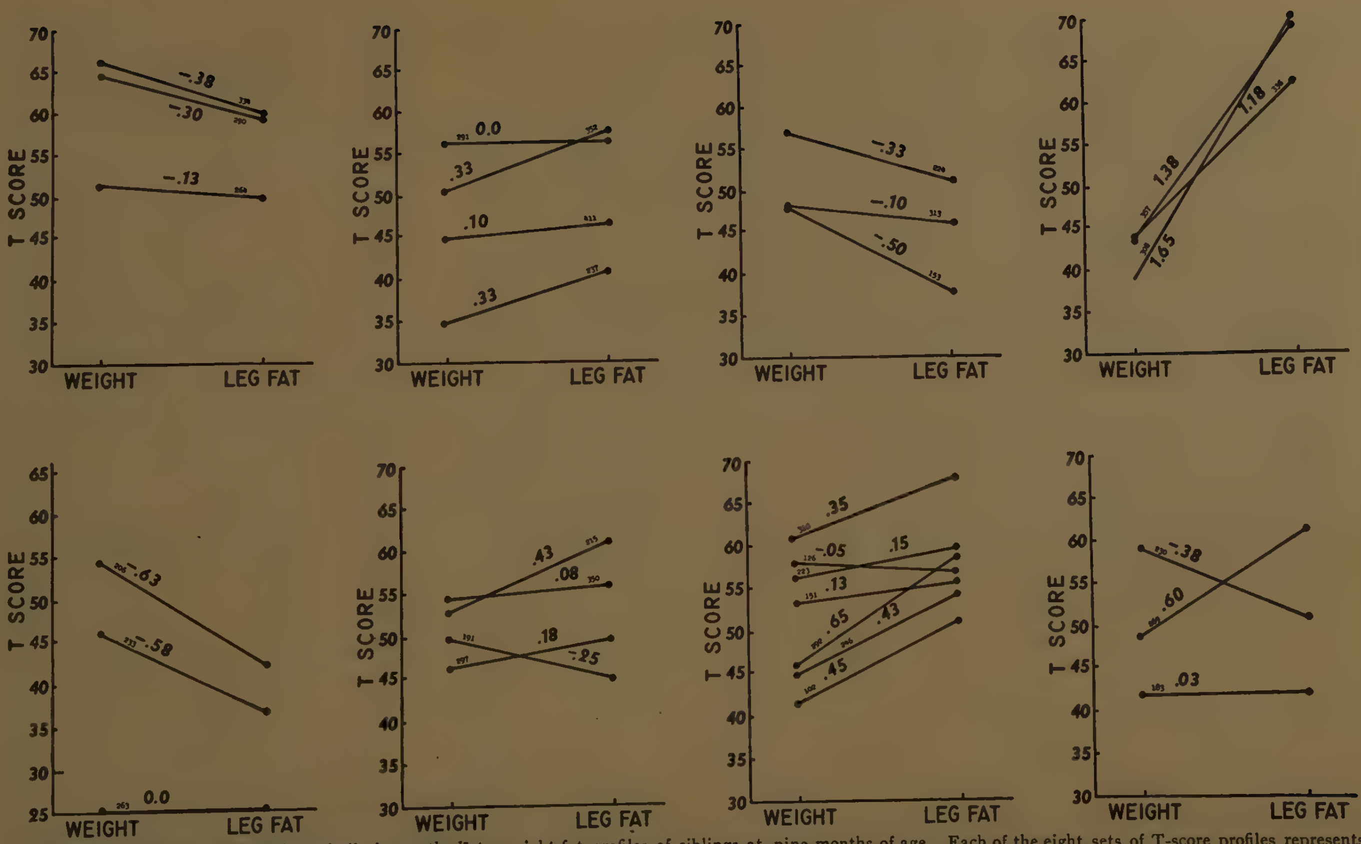

FIGURE 8. Adaptation of the slope-similarity method[7] to weight-fat profiles of siblings at nine months of age. Each of the eight sets of T-score profiles represents one set of siblings. For the 48 pairings shown, the mean *difference* in slope was 0.32 while, for 48 pairs of *unrelated* children, the mean slope difference was 0.54.

extent of pattern reversals. The visual method, however, is inadequate to cope with numbers of pattern pairs and provides no numerical measure of pattern similarity.

Various indices and coefficients of pattern similarity have been developed and reported (for a review, see Gaier and Lee[3]). Some of them are suitable for us where the items are uncorrelated, while others have been developed for highly correlated items.[3,5] One technique matches pattern profiles in terms of the slopes of corresponding segments of the patterns[7] (as shown in FIGURE 8, this technique is extremely applicable to comparison of sibling patterns during infancy). Others, like Cattels, $r_p$, measure the strength of the correlations among the scored values,[8] while still another method measures the mean difference between the $T$-scored values and their own means.

Two approaches to pattern matching have been reported in the recent anthropometric literature. One, developed by Sutton and Vandenberg, has been applied to urinary excretion patterns in human siblings and twins.[9] The other, developed by the author,[10] following the work of Lacey *et al.*,[11] has been applied to relative fat patterns. Both employ $Z$-scored values, and make use of the differences between pairs of $Z$-scored values.

The "similarity index" of Sutton and Vandenberg* is "the reciprocal of the mean square average difference in standard scores between siblings for all of the items measured."[9] Expressed mathematically, the similarity index equals

$$\frac{1}{\sqrt{\dfrac{\sum d_z^2}{N}}}$$

This measure emphasizes similarity in level more than similarity in configuration.

The author's measure is simply the standard deviation of the differences (in standard scores) between each pair of scores in the two patterns being compared. This value $\sigma d_z$ is

$$\sqrt{\frac{\sum d_z^2}{N} - \left(\frac{\sum d_z}{N}\right)^2}$$

It will be seen that in the hypothetical case where two patterns are identical and therefore spaced equidistant throughout, all values of $d_z$ will be equal and therefore $\sigma d_z$ will equal zero. Any other case involving pattern reversals, or variations in the $Z$-score differences between paired values will result in a larger value of $\sigma d_z$ (FIGURE 9). Thus $\sigma d_z$ has a minimum value of $\sigma$, and rises as pattern similarity becomes less. It emphasizes configuration often to the exclusion of level.

Obviously it is desirable to comprehend the meaning of a given value of $\sigma d_z$. In the author's initial application this was done by comparing the mean $\sigma d_z$ obtained for 13 before-and-after fat pattern pairs, with the mean $\sigma d_z$ obtained for

* While the Sutton-Vandenberg "Similarity Index" is appropriately titled, mention should be made of other measures of profile similarity bearing the same name. For details, refer to the summaries by Gaier and Lee[3] and Cronbach and Gleser[5] and table 1 in Cronbach and Gleser.

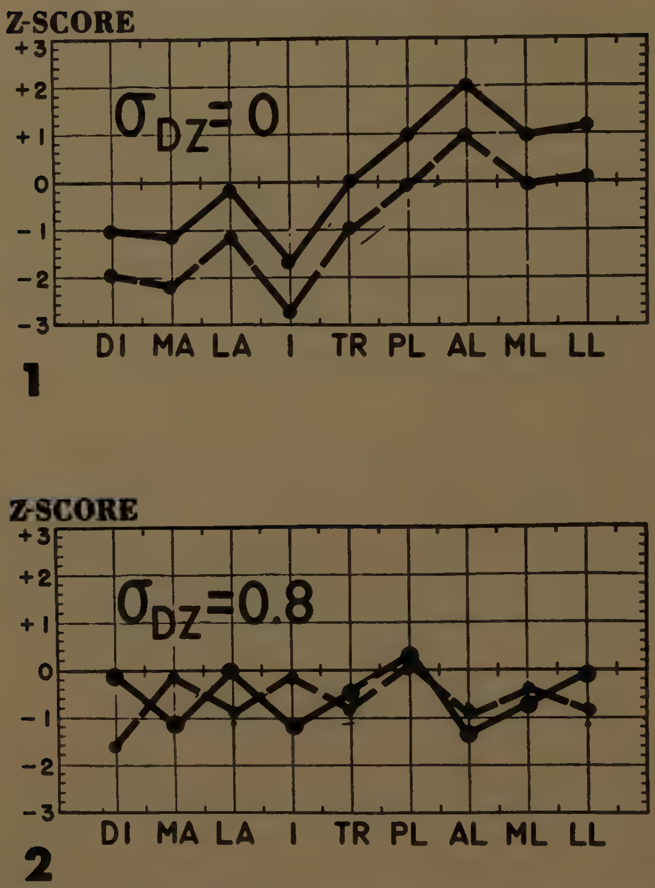

FIGURE 9. Two sets of hypothetical patterns illustrating the $\sigma d_z$ or "profile similarity index." The patterns shown in 1 are equidistant throughout, hence $\sigma d_z$ is 0.0. With moderate dissimilarity, including five pattern reversals, the value of $\sigma d_z$ for 2 is 0.8.

13 randomly-selected fat pattern pairs, and finally with the $\sigma d_z$ obtained for 13 weight-matched fat pattern pairs.* Thus it could be shown that the relative fat patterns of the same individuals before and after a 60,000 calorie debt showed greater congruence (despite a general fat loss) than the relative fat patterns of randomly selected individuals in the base population.

It should be emphasized, however, that the $\sigma d_z$ measure of pattern similarity, like the similarity index mentioned above, is a purely empirical measure whose properties are largely unknown. Among the objections that may be raised, are:

(1) The $\sigma d_z$ ignores levels, while emphasizing differences in pattern configuration.

(2) The influence of the number of items on the value of $\sigma d_z$ has not been considered.

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* The random pairs were selected by a disinterested observer (C.T.B.) to avoid bias.

(3) The effect of intercorrelations among the items has been ignored.
(4) The influence of pattern reversals has not been explored.
(5) The initial application constituted a uniquely monotonic situation.

Only the first objection can be safely answered, since the matter of levels may be ignored in anthropometry though not in psychometry. As to the remainder, while it may be demonstrated that pattern reversals dramatically raise the value of $\sigma d_z$ the new and untested nature of this measure of pattern similarity merits caution in its use.

### *Other Applications of Pattern Analysis to Anthropometric Data*

The specific illustrations employed in the last two sections by no means exhaust the applications of pattern analysis and the relative pattern technique to anthropometric data, or to other measurable data on human beings. For the phenomenon of patterning is universally present in nature.[12] Moreover, individuality is in essence uniqueness of pattern, somatic, physiological, and behavioral. And to the extent that the individual items are measurable, individuality may be expressed in the form of a relative pattern.

That people differ, and differ consistently in blood pressure, heart rate, and sweat gland activity has long been known. But it was the accomplishment of Lacey and his co-workers at the Fels Research Institute, to show that the response to stress is also patterned, characteristic of the individual, and reproducible to a high degree.[11] The autonomic response pattern thus characterizes the individual even more than the relative fat pattern, though the raw data are more ephemeral (FIGURE 10).

The various body fluids are also prime media for the study of patterning and individuality. The saliva, for example, contains a number of enzymes whose concentrations vary strikingly from individual to individual. The urine, which is available in greater volume, also shows large patterned individual differences in its constituents. Though day-to-day variations are often large, individuals do show consistency in the *pattern* of ketonic steroids excreted. And the work of Sutton and Vandenberg[9] puts in plain view the extraordinary similarity of sibling patterns of amino acid excretion (FIGURE 11).

But to return to the measurable dimensions that are more often included among "anthopometric" data, it would seem that further attention to patterns may be of considerable value. Few will deny that the measurement-by-measurement analysis of fossil men, in vogue since the Trinil bed first yielded Haeckel's postulated *Pithecanthropus alalus*, has complicated rather than clarified the taxonomic position of these nonsapiens hominids. Similarly, Newman's attention to the weights and statures of monozygotic twins ignored the fact that both may be reflections of nutritive status while, in twins reared apart, pattern rather than size might prove the constant.

In regard to growth, both absolute patterns and relative patterns should have their value. The absolute pattern, whether for subcutaneous fat or the six long bones, pictures changes with advancing age and maturational status. On the other hand, the *relative* pattern may make it possible to follow individual children through the complex of changes that constitute growth and develop-

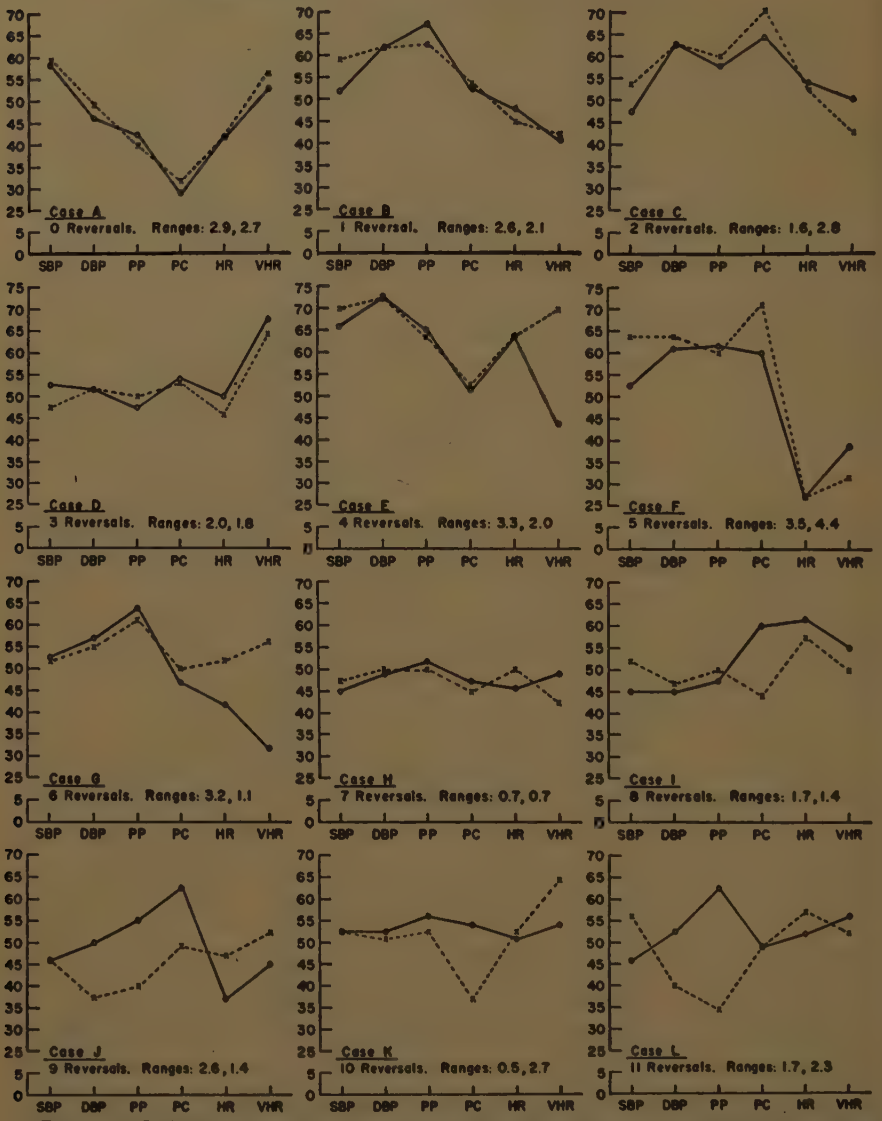

FIGURE 10. Individual autonomic response patterns. Under conditions of stress there are marked individual differences in the patterned response to stress. And these patterns show high test-retest consistency (from Lacey and Van Lehn,[11] with permission). For the physiologic variables measured, refer to the original paper.

ment. Does the relative fat pattern hold constant from childhood through age? How similar are the relative fat patterns of siblings of unlike sex?

Finally, through the use of relative patterns rather than individual measurements a useful racial anthropometry may yet emerge. While this is a statement of likelihood, rather than a sage prediction, the fact that such patterns are

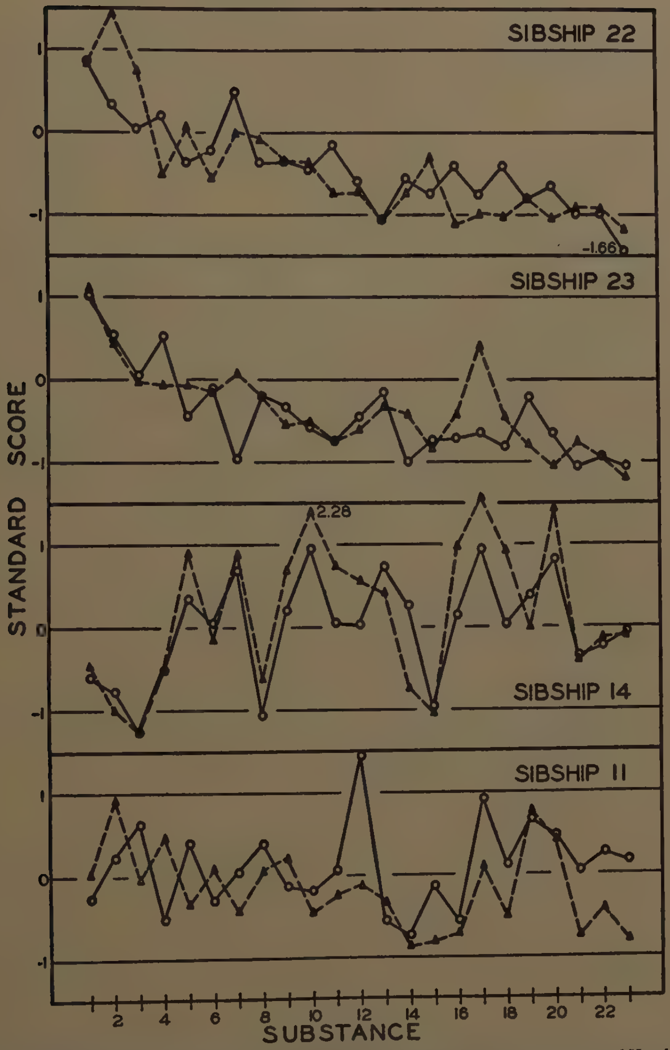

FIGURE 11. Sibling similarities in urinary excretion patterns, reprinted from Sutton and Vandenberg[2] (with permission). Here all values are expressed in standard scores, and the numbers on the abcissa refer to urinary constituents and constants.

based on standard deviation units (thus correcting for differences in variability) is an important one. Well-nourished and poorly-nourished individuals of the same strain are not completely different. Though they differ both in gross dimensions and segmentally, they should preserve enough patterned similarity to show their genetic relationships on *Z*-score or *T*-score plots.

## *Conclusion*

It has been the purpose of this paper to discuss, and to illustrate with some few examples, the applications of pattern analysis and pattern matching to anthropometric data. This is not to deny the value of the measurement-by-measurement approach. Nor does it compete with the various ways of relating the size or growth of one body segment to another. Rather, pattern analysis adds a further dimension to the utilization of anthropometric data, and makes possible solving some anthropometric problems not easily resolved in other ways.

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# BODY DYNAMICS AND DYNAMIC ANTHROPOMETRY

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Man exhibits some of his most distinctively human characteristics in his pattern of motion. The ease with which he spans distance and executes intricate maneuvers testifies to the harmony that exists between the construction of the body and its motor mission.

Quantitative appreciation of the human mechanism antedates both anthropology and biophysics and is not the exclusive property of men of science. Calipers and equations cannot compete on even terms with the experienced eye in evaluating patterns of esthetic conformation. Scientific methods manifest their superiority when more subtle relationships are sought, such as those encountered in the dynamics of movement.

It is only after attaining some degree of familiarity with the body in motion that one begins to appreciate the extent to which the proportions we measure in the body at rest owe their existence to satisfactory performance as parts of the dynamic mechanism. Certainly, the human body from the neck down is heavily indebted to the selective influence of motor performance in guiding its evolution. Even the skull has adapted to locomotor posture, and the brain it enshrines has added complexity to guide more intricate movements.

Appreciation of the human being as a locomotor mechanism can be enriched by many quantitative approaches. Characterization of individuals by the speed with which they traverse distance is an example of early dynamic anthropometry. Facility in starting and stopping, a measure of the application of accelerations, is of interest to the spectator in athletics and to the individual himself when competing with traffic. Still another useful approach is through energy exchange, with measurements of oxygen consumption and heat production providing convenient data.

More congenial to the physical anthropologist as a starting point for a reconnaissance of human movement is a consideration of the physical characteristics of the mechanism. With this mechanism he already has personal and professional acquaintance, and many of its components he has measured. Now he finds that their motor function can be reflected best by measurements of different design. The dimensions of skeletal elements most useful for the selection of drawers in which to keep them need not be the best gauges of their contribution to movement.

## *General Plan of the Mechanism*

Fundamentally the human mechanism consists of a series of bony levers connected with each other by joints, as illustrated by the lower limb in FIGURE 1. Each bony lever constitutes a link in the mechanism, the body as a whole being a family of links. The joints are so constructed that the only movement each link is allowed is rotation with respect to its neighbors. Even movements as simple as the vertical lifting of the trunk, in progress in FIGURE 1B, are actually effected by a series of rotations.

The length of each link is a measurement of primary importance and is defined as the distance between the centers of motion of the joints situated at either end of the link. For the femur, this functional length is the distance from the center of the head of the femur to the axis of the knee joint, as may be seen in FIGURE 1. The fact that the knee joint is not cylindrical and its axis consequently shifts as the knee is bent emphasizes the dynamic nature of this measurement even when made on a dead bone.

Individual specifications of the numerous links that complete the human mechanism need not be catalogued here. More urgent is a focusing of attention on the fresh insight that rewards each application of a functional attitude towards the human body. The functional lengths of femur and tibia represent attributes of these bones different from those specified by traditional anthropometry. The closeness with which thigh and shank equal each other in length when measured from joint center to joint center is more useful to artists drawing the human figure than are the conventional bony proportions. The geometry of the femur springs to life for the student when the theoretical mechanical axis is provided to him as a reference line by the insertion of wire or cord. Emphasis on the virtues of the measurement of these mechanical features of bone should not lead us to minimize the value of traditional anthropometry. No one set of measurements of any bone can reduce to numbers all of its qualities that merit our interest.

In addition to their linear dimensions, the body links are characterized by the amount of tissue included in them and the manner in which this tissue is

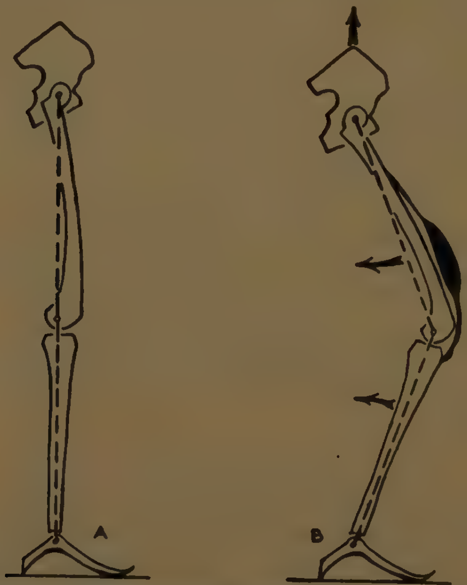

FIGURE 1. The elements of structure of the human mechanism are illustrated by the lower limb, shown erect in FIGURE 1A and slightly crouched in FIGURE 1B. The lengths of the bones as links in the mechanism are indicated by the broken lines joining the joint centers. The arrows in FIGURE 1B show the directions of movement as the individual resumes an erect position; in order to lift the pelvis straight upward, the femur and tibia undergo rotations. The power for these rotations is provided by the only muscle shown, a knee extensor.

distributed. The description of these characteristics requires the measurement of the weight of the part, the position of its center of gravity, and its moments of inertia. When this has been done, we have achieved the cursorial concept of man shown in FIGURE 2. The links now not only have length and direction, but their weights and moments of inertia are symbolized by the spheres surrounding the centers of gravity.

The physical constants that pertain to the individual links of the mechanism can be used to measure the differences between individuals. They also call our attention to some fundamental features of human design. Historical interest attaches to the early measurements of Braune and Fischer (1889, 1892) and the discussion of them contained in Fischer's outstanding theoretical book (1906). The tendency of the center of gravity of the major links to divide the distance between proximal and distal joint axes in the ratio of 4:5 is a quantitative expression of the degree to which muscular tissue is concentrated proximally. The practical advantage of this arrangement is evident when we remember what happens to our extremities when we load them distally with heavier footwear. The attention of those who are interested in body types should be called to the fact that the moments of inertia of the body as a whole can be determined instrumentally for specified postures and could prove interesting as a measure of distribution of mass.

### *Motor Power and Control*

Having surveyed the architecture of the mechanism by which locomotion is accomplished, we are ready to consider the forces that apply energy and provide control. These forces are chiefly of two types—gravity and muscle.

Gravity differs from muscle in that it is fully predictable, acting forever, al-

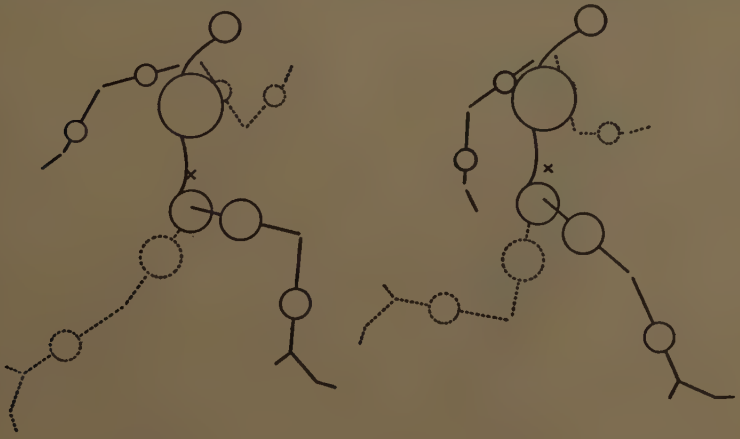

FIGURE 2. Two phases of a man running show his body in action. The links of his mechanism are shown as lines with circles drawn about the center of gravity of each link to show the distribution of mass. For facilitation of computation, forearm and hand were grouped as one unit, as were also shank and foot; the useful grouping depends on the object of study. The instantaneous position of the center of gravity of the entire body is marked "x." Based on data from Elftman (1940).

ways in the same direction. The effect of gravity, therefore, depends on the angle of inclination of the object on which it is acting. Taking FIGURE 1A as an example, with the center of gravity of the body balanced vertically above the ankle joint and knee joint, gravity will compress these joints but will have no lever arm for rotating either thigh or shank. When the position of the body has been changed to that of FIGURE 1B, both thigh and shank are inclined, providing gravity with a lever arm by means of which it tends to accelerate their further rotation.

Had the individual shown in FIGURE 1B surrendered to gravity it would have seated him promptly on the ground. Not wishing this to happen, he stalemated gravity by telling his knee muscles to stimulate enough fibers so that they would produce a moment of force equal to that of gravity but acting in the opposite direction. By subsequently increasing the number of fibers stimulated, he was able to raise himself as indicated in the diagram.

Recognition of the fact that intelligent control of even the most ordinary human movements depends on our muscles lends dignity to their study. The 40 per cent of the human body devoted to muscle has long been favorably received by cannibals; it is time that the civilized world added its appreciation. Muscle, unlike gravity, can stand idly by until its action is needed. It is under the control of the nervous system instead of being dependent on the inclination to the vertical, and the force that a muscle exerts can be varied to suit the occasion.

The energy transactions of the body are controlled by muscle. Gravity will help pull a body down but resists its efforts to rise again. The only way to profit from gravity is to keep on going downhill. Muscle is more adaptable

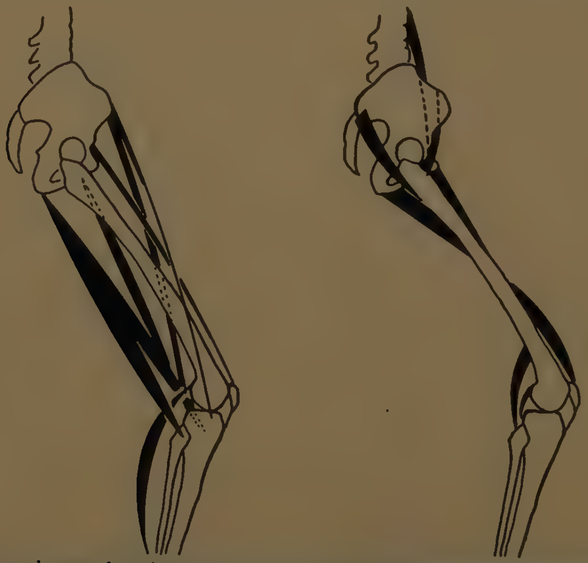

FIGURE 3. Preponderance of two-joint muscles in the human thigh is emphasized by showing them in the diagram at the left with the one-joint muscles relegated to the diagram at the right. Modified from Elftman (1954).

in its habits. When a part of the body requires speeding up, muscle can help by shortening, converting chemical energy into mechanical work as it tugs. If the part needs slowing down, muscle can do this too, the energy absorbed as the muscle is stretched being dissipated as heat.

These properties of muscle are mirrored in its arrangement in the body and therefore find expression in static shape as well as in dynamic function. Concentration of muscle tissue proximally in each link has already been noted. Provision of appropriate lever arms to alleviate the difficulties otherwise imposed by length-tension relationships is responsible for other details of body construction. Even the shape of the thigh, which it owes largely to the preponderance of two-joint muscles illustrated in FIGURE 3, finds its explanation in the saving in energy expenditure that they make possible.

### *Dynamics and Anthropometry*

It is time to summarize response to the question: What light does the study of movement throw on the qualities that we appreciate in the human body? The answer is of equal interest to the anatomist and the anthropologist, allowing some difference in emphasis. The anatomist is concerned chiefly with those features of structure that are necessary for the function of all individuals, and he accepts variation, with regret, as a characteristic of nature that complicates an otherwise lucid picture. The physical anthropologist finds variation between individuals intrinsically delightful and makes his living by its study. It is his privilege and obligation to sense the nuances, even in motor manifestations, that add savor to personality.

The erect posture of man has delegated to his lower limbs the responsibility for carrying him from one activity to another. This has emancipated his hands for the more delicate motor operations that have been so successful that both

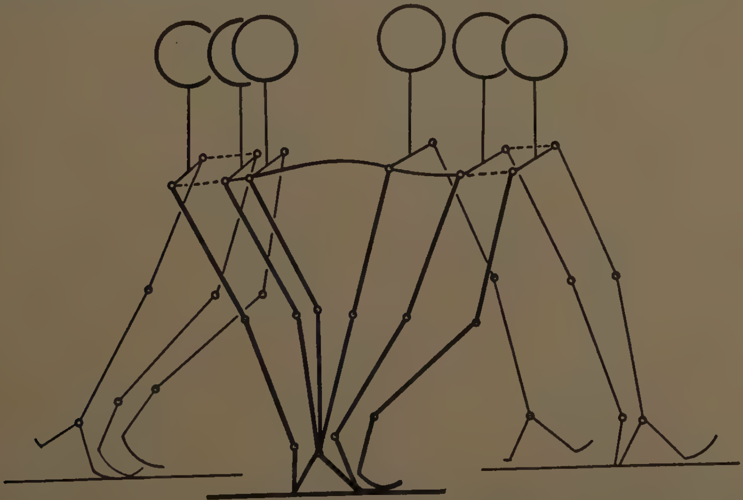

FIGURE 4. Man walking. Some locomotor features of the human mechanism are represented here to summarize their contribution to man's structure. This diagram is modified from Elftman (1954), to which the reader is referred for a more technical discussion.

handling and manipulation are now used to describe processes far removed from the sphere of body mechanics. The selective criteria that have guided the evolution of man's arms and hands through the ages have relied just as confidently on the dynamics of movement as have those that have shaped the lower limbs.

Any one point of view can provide only partial insight into the nature of man. That provided by a dynamic approach to human locomotion is epitomized by FIGURE 4. Not all the characteristics of the human being are concerned with his particular type of movement. But without this particular type of movement to guide his evolution, we should not have modern man.

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# THE ANTHROPOMETRY OF BODY ACTION*

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Conventional anthropometry of the adult has been limited largely to measurements that may be made with the anthropometer, the tape measure, and the calipers. The dimensions are linear, and they relate to the body surface—heights of body landmarks, widths, circumferences, and spans between surface points. To be duplicable, the measurements must be made in the same manner on different individuals, and the subjects must assume a stereotyped static posture, usually standing, during measurement. Supplementary and equally stereotyped postures such as sitting, supine, arms outstretched, *etc.*, may also be used. The measurements, of course, allow comparisons between individuals and between population groups. They provide information on the relative magnitude and variability of individuals, but they are in no way functional measurements.

If a dynamic anthropometry is to be developed that can cope with problems of movement and postural change, new methods must be sought, and the parameters of measurement must be extended to include angles, velocity, acceleration, rhythmic patterns, space envelopes, and force. Body activity is infinitely variable, and it is essential that there be a theoretical framework so that relevant and secondary features may be evaluated correctly. Similarly, it is important that the conditioning factors and inbuilt limitations of the body machinery be also understood. Simplifications and abstract concepts are necessary, but it is important that these should not be oversimplified relative to the specific problem at hand.

Studies based on dynamic measurements should contribute to human comfort, efficiency, convenience, and safety. One may envision the application of work-space information to the industrial worker, to the school room, to vehicles and machinery, and to military problems. There should be contributions to furniture design and to the architecture of such work spaces as kitchens and bathrooms. In addition, a better understanding of dynamic actions of the body mechanism should provide help in the coaching of athletic performance, in the design of work clothing, including shoes and gloves, in personnel selection, and in the designing of prostheses.

Braune and Fischer[6] were pioneers in this field, and more recent work has been done by Lay and Fisher,[26] Hooton,[21] Randall *et al.*,[31] King,[22] Chapanis *et al.*,[8] Smith and his group,[33] McFarland *et al.*,[28] and Dempster.[11]

## *Bone Functions in Body Mechanics*

Bones have many functions: they are reservoirs of calcium, phosphorus, and carbonate; they house the bone marrow, which produces the red blood cells, leucocytes, and platelets of the blood; they provide processes and expansions

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* A study conducted under contracts with the Wright Air Development Center (Section of Anthropometry) Wright Patterson Air Force Base, Dayton, Ohio, and with the United States Office of Naval Research, Washington, D.C.

for muscle attachment and leverage; they grow and mature, and their form is responsive to diet, to hormones, and to persistent and intermittent forces. These features, however, may be ignored here as irrelevant to the mechanical essential of rigidity. Forces may be transmitted along or across the rigid substance of bone. Bone has a tensile strength and modulus of elasticity in tension like walnut or hickory wood. It is as strong as concrete in compression, and its compressive modulus of elasticity is comparable also.[12]

Within the range of ordinary behavior, bone may be considered as a competent rigid material. It spans the articulations and separates the joints by fixed distances. Moreover, the ends of the bones, where adjacent bones attach, are molded into specific configurations (FIGURE 1) that permit unique types and directions of movement.

Bones form the essential levers of the body system. Although tensile or compressive stresses are transmitted along the substance of the bony material, the effective levers for rotatory actions follow straight lines between one joint center and the next in sequence. In the femur or radius, such straight lines between joint centers actually fall in part outside the limits of the curving shapes of the bony substance. Where both ends of a bone have rounded (*i.e.*, convex) articulations, the line goes from center to center within the length of the bone. In certain locations such as the forearm and leg, the lines span from a joint center located in the more proximal bone, *i.e.*, in the humeral or femoral condyles, through the whole bony support of the segment in question to a center in the adjacent distal bone in the hand or foot, that is, through a chain of three bones. These spanning distances between adjacent joint centers are the functional equivalent of the "links" of the engineer.

### *The Body Link System*

The engineer commonly regards links as parts of a two-dimensional system that might be diagrammed on paper. The articulating parts overlap and are joined by pins, which act as axes of rotation (sliding-plane and helical joints sometimes found in machinery may be ignored here as special classes that are of little concern in the body system). The link is a line of constant length that spans the pin axes. It is a functional dimension dependent upon the rigidity of the material that separates the centers of rotation. The metal parts of a machine per se are not links. A link is merely a line—an abstraction—that may execute only those angular displacements allowed by the joint elements.

In the machinery of the engineer, the links move in relation to a framework, and this framework becomes, in reality, an additional link that interconnects the others. In order to transmit power, the linkages of machinery must form a closed system in which the motions of one link have determinate relations to every other link in the system. The closed system assures that forces are transmitted in positive predetermined ways and in no other.[32] The study of the relative motions of the links of machinery forms the subject matter of kinematics, a powerful tool for the design and improvement of mechanisms of all types.

In engineering, a background of kinematics gives understanding. It should likewise have value in relation to body motions.

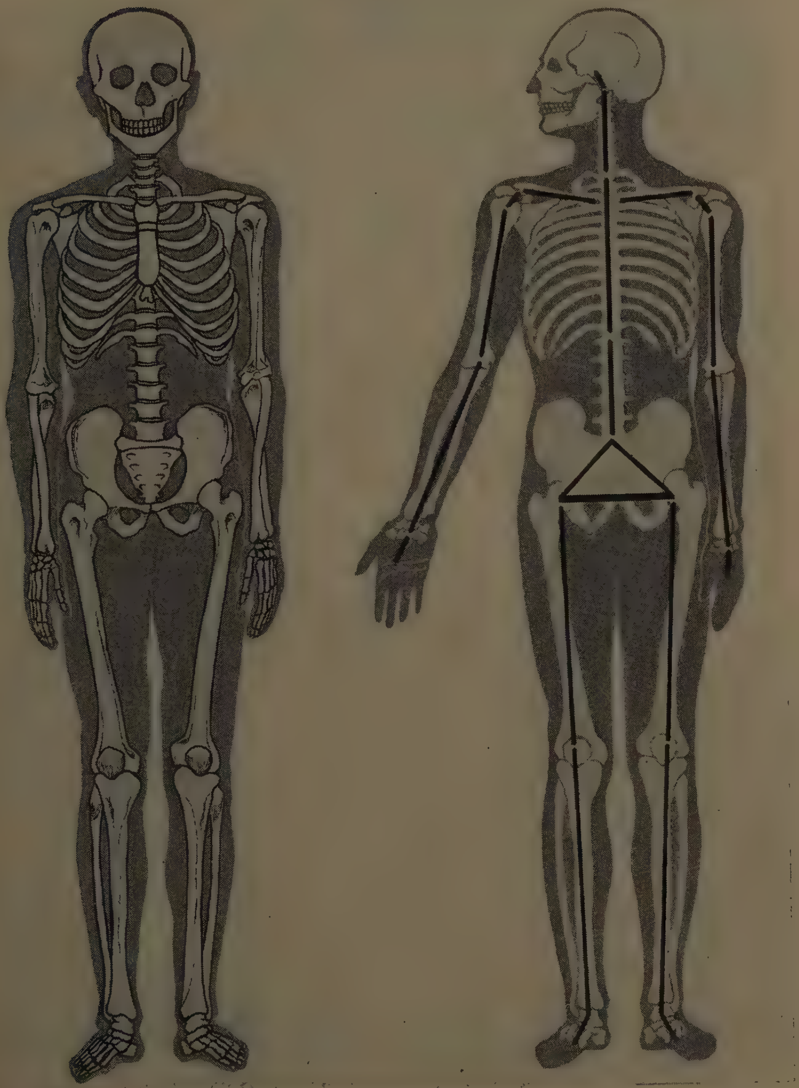

FIGURE 1. Left, human skeleton; right, plan of body links.

The body links rarely overlap, and none is truly pin-centered. In the major limb joints, the contiguous articular surfaces slide relative to one another as the bones rotate about a center in one or the other of the bones. The surfaces, although pressed together by the variable forces of ligaments, muscle, and atmospheric pressure, are ordinarily only partially congruent, since the curvatures are not truly reciprocal. Nevertheless, the areas that do contact as the articular surfaces slide against one another either inhibit or permit free rotatory motions in particular directions. Most of the joints have a freedom for angular motion in different directions, and power transmission is quite impossible without the accessory stabilization of joints by muscular action. Strictly predictable, determinate motions of the linkages as found in closed-chain systems are found at very few joints, *viz.*, radio-humero-ulnar, carpal, tarsal, and thoracic joints. The open-chain (indeterminate) system, as Fischer[18] indicated, predominates in the body mechanism.

Because of the basic differences between the links of the engineer and those of the body system, certain characteristics of the latter should be outlined. The body link is the straight axial line or core line that extends through a body segment. Its integrity depends upon the rigid substance of the bone, and it terminates in axes about which the adjacent links rotate. The skeletal elements may be reduced to produce a stick figure like that of FIGURE 1. The anatomical specializations of bones for muscle attachment and joint articulations, important as they are for body functioning, may be ignored in considerations of simple link motions. The bone may flare out or bend away from the core line between adjacent joint centers. The femur, for instance, has its eccentric greater trochanter, the scapula its blade, spine, and acromion, and the elbow its projecting olecranon process. These are important for the muscular control of link movements, but they are entirely secondary to the basic kinematic system of the body segments.

The complex structure of the pelvis with its visceral basin, its birth canal, and its wide areas for muscle attachment may be simplified to a single link though, in this instance, it is triangular, with articulations to both the right and left femoral links and to the vertebral chain of links. Although the thorax may be treated as a separate system of linkages for purposes of the study of the respiratory movements, it may, for gross postural purposes, be simplified to the vertebral links (perhaps even treated as a single link) and a bucket-handle type of upper sternocostal linkage bridging from the right to the left of the uppermost thoracic vertebra (FIGURE 7). The latter permits linkage connection with the clavicular links of each side.

Since the link concept has pertinence for the analysis of rotatory motions, it should be apparent that the type of analysis anticipated should determine the degree of reduction to be used. In FIGURE 1, certain obvious linkages have not been shown, as for instance finger and toe links, a forearm link between the radius and ulna, separate links between successive vertebrae, and linkages between the ribs and sternum. The remaining links are probably adequate for most purposes of postural analysis.

The system may be diagrammed on paper, or it may be treated as a three-dimensional stick figure. On paper, the angular motions of links may be diagrammed with the aid of a pencil compass. The links can be laid out on frame-by-frame records from motion pictures of actual subjects or from stroboscopic photographs of body movements. The movements of parts are most easily analyzed as motions in a plane. Links are linear and their angular movements sweep over surfaces. If the latter are curved, or are not in the plane of reference, they may be projected to suitable rectangular coordinates.

Rotations about the longitudinal axes of the segments are permitted in the trunk and at the ball-and-socket joints of the hip and shoulder (glenohumeral joint), at the shoulder girdle joints, at the forearm joints, and at the knee. These movements may be important functionally, and they can be analyzed further. In general, however, such movements are less gross than other rotations in the sense that they involve small moments of inertia. To this effect, the forearm (radio-ulnar joint system) may for many purposes be considered as a single link between the elbow and the wrist (FIGURE 1).

### *A Plan of Body Linkages*

The "link" man of FIGURE 1 is presented as a simplified kinematic system subject to further extensions as required for specific problems. The 25 vertebral links above the sacrum have been reduced to 3 links: cervical, thoracic, and lumbar. The head link articulates with the cervical. The triangular linkage of the pelvis connects with both the lumbar link and the two thigh (or femoral) links. The sternocostal bucket-handle linkage articulates with the clavicular links and these, in turn, with the scapular links. The latter linkage represents a straight line between the mean center of scapula rotation, relative to the clavicle (on the acromioclavicular and coracoclavicular joint system) and the mean center of glenohumeral rotation. Next comes the humeral link, the forearm link, and the hand link. In the lower limb, the chain of links consists of a femoral link, a shank link, and a foot link.

The hand, foot, and head are end links beyond terminal joints. At the hand, the link might be variably referred to as the linkage between the wrist center and a functional contact point at the heel of the hand, the knuckles, the ball of the thumb, or the finger tip. The foot link might span the ankle center and the heel, or the ankle and the ball of the foot or toes, *etc.* In general, however, where free movements of the end members are concerned, the parts may be regarded as cantilever systems, and the link span may be regarded as the straight-line distance from the terminal joint to the center of gravity of the part.

The center of gravity of the head lies at the midsagittal plane on a line that interconnects points anterior to the tragi of the ears. The head link extends from this point to the occipitocervical junction. The hand link passes from the wrist center to the "V" between the radial longitudinal and proximal transverse palmar creases in line with the third finger. For the foot, the link terminates halfway down along a line from the ankle center to the ball of the foot in the plane of the second toe.

Mean link dimensions may be visualized as beginning and ending in functional joint centers (or centers of gravity of terminal members). Since these end points are not structural landmarks, the link lengths cannot be measured directly on the static subject. The systematic manipulation of joints permits a fair approximation for the location of mean joint-center positions. More elaborate methods for locating joint centers, based upon cadaver joint preparations and involving geometrical techniques (*vide infra*), measurements of bone dimensions, including articular curvatures and extrapolations for specific bone lengths, are possible (TABLE 1). But these are not truly routine anthropometric procedures. Fortunately, the linear dimensions are less significant than angular measurements of link movement.

The link figure presents the essentials of the dynamic man. The links are the basic units to which the angular motions of the body parts may be referred in the multiplicity of body postures and motions. A dynamic anthropometry that is not consistent with their functioning cannot claim more than limited empirical value.

### *Links and Dynamic Aspects of the Body*

The body is predominately an open-chain system of links. The links rotate about joint centers and exhibit a variety of angular positions consistent with the range of motion permitted by the joints before restraining mechanisms impose limits. An open-chain system cannot produce determinate or strictly predictable motions. The end member may have an infinite number of positions relative to the trunk allowed by the cumulative range of the more proximal joints.

There are advantages in such a system. A part may be placed at a variety of point positions in space. Reach becomes a meaningful function, and balancing reflexes become an essential in the antigravity mechanism of postural maintenance. The body is permitted such motions as kicking, walking, throwing, and the use of tools. Muscular action may stabilize certain motions momentarily at one or another of a chain of joints. Such stability allows the body to concentrate the prime motion of other muscles on specific joints and on specific planes of action. By this mechanism, force applications, accurate throwing, the use of tools, writing, and other animal and human activities become possible.

The fingers of the two hands may be interlocked to interconnect the right and upper limb links; the legs may be crossed for seated stability; the arms may be crossed or placed on the hips. In such actions as these, temporary approximations to closed chains are effected. Between certain of the links concerned, however, there are soft (nonrigid) tissues. These, in turn, are pressed together to a variable extent, so that interposed skin surfaces make a friction contact. Clothing, gloves, or shoes next to the skin surface will more often decrease than increase the friction contact.

Link chains may be cross-connected, as in crossing the knees (*viz.*, pelvis and right and left thighs) or in placing the hand on the same or opposite shoulder. To the extent that these temporary closed chains approximate a triangular linkage, there is a degree of stability imparted even without muscular actions, but this is still approximate because of the interposed soft tissues. The closer the links approximate a closed triagular, or pyramidal, pattern, the less muscles are called upon for stabilizing action at joints. One may recognize many rest positions involving this principle: crossed arms, hands in pockets, or such sitting positions as crossed knees, ankle on opposite knee, elbow on knee, or head in hand. The dog sitting on his haunches and other quadrupeds show different rest positions. As additional joints come into the linkage, the accessory tensions of muscles become more and more important for stability or for directing forces in specific ways.

Temporary closed chains that involve extrinsic environmental objects also may be recognized. For instance, the two arms using a pruning shears are such a linkage. When a seated person operates a foot pedal, the closed chain involves the shoe sole, the soft tissues of the foot, the foot and limb links, the pelvis, the nonrigid buttock tissues, the seat, the floor, and the pedal. In the operation of machinery by a hand lever, there is a complex linkage involving the machine links, its frame, the floor, and the body links from foot to hand.

These temporary closed chains can be only approximations to determinate systems, since there are nonrigid tissues between certain links. In addition, the variability of possible motions at most of the joints requires muscle actions that vary with the style of neuromuscular control that an individual may employ. The open-chain system of the body insures unpredictability of action. It allows a variety of selective and discriminatory actions in the transmission of forces. The accuracy and power of control is based upon neuromuscular physiology, and psychological factors cannot be excluded.

The links are functional dimensions rather than structural entities. They represent deep-lying relationships of the joints, and the standard anthropometry involving surface landmarks is quite unrelated to them. Angular motions of the links may be studied, and measurements of the space requirements of the tissue-enclosed kinematic system of the body may be devised. The planning of such measurements, however, requires an understanding well beyond structure alone.

### *Joints in Relation to Link Movement*

Descriptions of the anatomical structure of the joint elements that interconnect the link members are readily available. The configuration of bones and their cartilages at the contacting regions of the joints predetermines the directions in which links may rotate. When muscle tensions or the superimposed weight of the body acts across a joint, the contiguous surfaces are pressed together. The shape of the contact or the ligamentous bindings either allow or eliminate certain types of angular movement. At the elbow, the forearm joints, or the ankle (tibio-talar joint), movements are restricted to specific guided paths of rotation from which there is no deviation.

At the elbow and ankle, the movements are generally referred to as flexion-extension movements, but in each instance there is a sequence of slight contingent movements not limited to the sagittal plane. Nevertheless, the movements are guided from instant to instant, and angular movement can continue or reverse along only the guided path provided by the joint structure. In such joints, extraneous movements are prevented by the wedging of the bony configuration, and there is but one degree of freedom for rotational movement allowed. In FIGURE 2, the members of the elbow and forearm joints have but one degree of freedom of motion.

At the wrist, the hand may flex and extend or move at a right angle in abduction or adduction, but free rotation about a longitudinal axis is virtually eliminated. At the knee, both flexion and extension movements and rotational movements of the shank are possible, but lateral movements do not occur except for a limited range where the ligaments are momentarily lax. In each instance, the predominant movements involve two degrees of freedom (FIGURE 2). At the ball-and-socket joints at the hip and shoulder (glenohumeral joint),

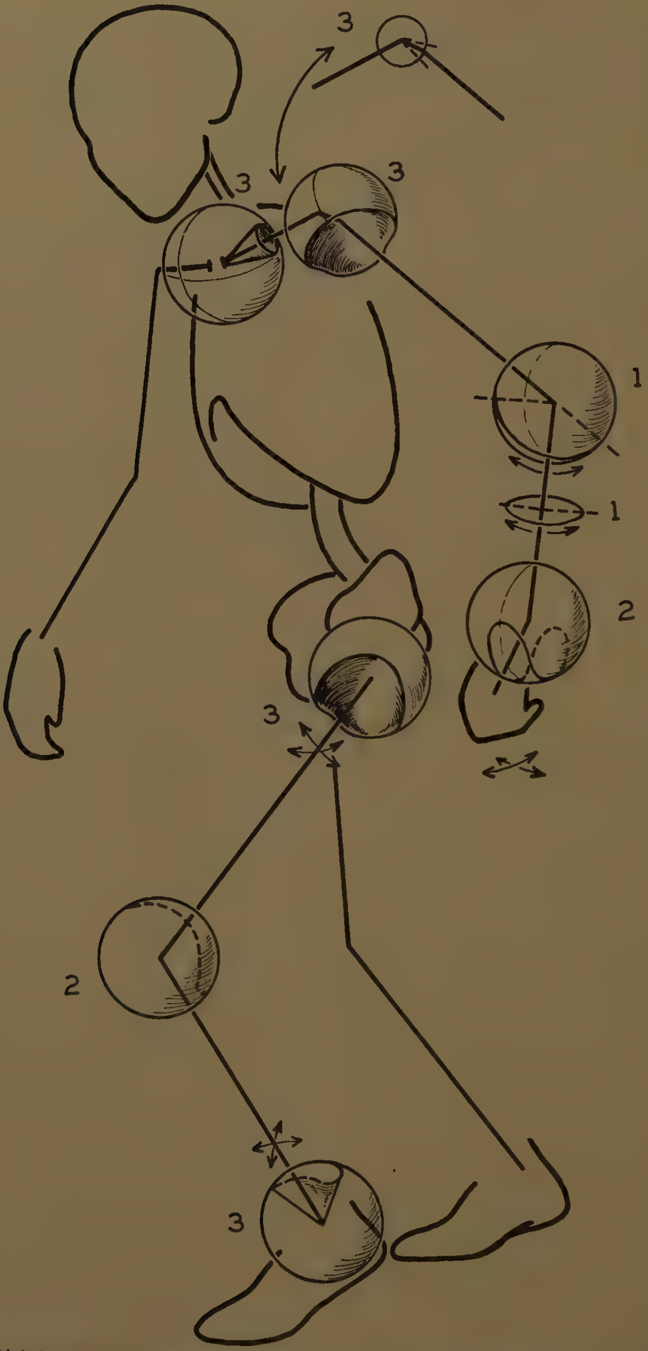

FIGURE 2. Link figure with globographic representations of the joint ranges of the extremity links.

there may be inward or outward rotation about the axis of the femoral or humeral link, or there may be movements in the sagittal plane (flexion-extension), or in the transverse plane (abduction-adduction). There is no restriction to the direction of rotation except at the limits of joint range. One may speak of three degrees of freedom of rotational movement. In the subtalar joints of the foot, at the claviscapular joint system (the functional equivalent of the composite coracoclavicular and acromioclavicular joints), and at the sternoclavicular joint, one finds three degrees of freedom at each joint. The analysis might be carried further to the finger and toe joints and to other joints of the trunk, but this is sufficient for illustrative purposes. Fischer[18] spoke of the degrees of freedom at joints, but this convenient approach has seldom been followed by writers in the United States.

One may note the cumulative pattern of degrees of freedom in a proximodistal sequence: upper limb—3/3/3/1/1/2, and lower limb—3/2/1/3 (FIGURE 2, however, further simplifies ankle and foot movements in one globe). There are 13 degrees of freedom between the trunk and hand, and 9 degrees between the trunk and foot sole. The sequence in the pattern of motion and in the degree of freedom of succeeding joints differs in the two limbs. Thus the elbow bends on a transverse axis, the forearm rotates on a longitudinal axis, and the wrist has (virtually) no axial rotation. The knee permits bending on a transverse axis and rotation on a longitudinal tibial axis, the ankle axis is approximately transverse, and the lower joints in the foot have rotational axes in several directions.[20]

## *Range of Joint Movement*

The type and amplitude of movement differs from joint to joint. All movements are rotational rather than translatory, and they are to be measured in degrees or radians. In each instance, ligaments, bony stops (elbow), tissue bulk (knee flexion), or muscle stretch define limits to the range of movement. The functional ranges are based upon anatomical structure, and they are variable from individual to individual. Measurable differences in flexibility are to be expected, due to age, sex, disease, and possibly race and occupation.

There is a literature concerned with the systematizing of terminology and with techniques for measurement for clinical purposes. Instruments and methods have been described, but authors in general have been content with working values rather than with detailed descriptions of movements applicable to specific populations. Exceptions to the general pattern are: Sinelnikoff and Grigorowitsch,[35] Glanville and Kreezer,[19] and Dempster,[11] but even these are incomplete as full coverages of the different joints.

The dynamic anthropometrist should be able, in the future, to provide improved measurement values for the various joints. It would be inadvisable, however, to plan a battery of measurements without a sound functional knowledge based upon experience with cadaver joints.

Various authors have quantitatively studied the range of movement of the principal joints of the limbs on joint-ligament preparations of cadavers. Such data have been presented by: Strasser and Gassman,[37] Fick,[17] Shiino,[34] Braus,[7] Pfuhl,[30] Steindler,[36] Mollier,[29] von Lanz and Wachsmuth,[38] and Dempster.[11] Most of the work in the literature applies to the shoulder, hip, and knee joints.

The Albert-Strasser globographic presentation has been commonly used (Albert,[2] Strasser, and Gassman[37]). In this method, one of the bony members of a joint was clamped fast with the approximate functional center of the joint at the center of a large protractor system. The free member was swung to its limits in each direction along the protractor, and the maximum range of movement of a needle point marker on the moving part was recorded. This was repeated also for other meridians at measured angles from the first. These ranges were marked off at appropriate places on a globe provided with a scale of parallels and meridians. Where a joint presented three degrees of freedom of motion, the amplitude of movement along the long axis of the moving member was simply marked at points on the surface of the globe. The circumscribed area on the surface of the globe, corresponding with a solid angle originating at the globe center, described a bounding surface within which the moving part was unhindered. This shape has been called the excursion cone of the joint[25] or joint sinus.[18]

FIGURE 2 shows such globes at the principal joints of the limbs. Each globe may be regarded as fixed to one of the joint members, with the excursion cone so placed that the other member is provided with a guide or template that permits only a circumscribed amplitude of joint movement. (Except for the knee and foot, where the globe is affixed to the distal member, the proximal part of the joint at the other globes is fixed with the distal part moving within the excursion cone.) Where there are three degrees of freedom, rotations of the moving member about its own axis are possible, but the extent of this has not been specified in FIGURE 2.

At the ball-and-socket joints, there are contingent restraints to movement at the limits of the excursion cone. When the free member is twisted on its long axis to the limit in one direction or the other, the excursion cone for the remaining degrees of freedom may be characteristically widened or narrowed at one point or another of its boundary. Conversely, as shown in FIGURE 3C, if the free member (humerus) is moved to the maximum limit of the excursion cone, the bone rotates so that its front surface comes to face in different directions. FIGURE 3C shows movement at the glenohumeral joint (three degrees of freedom). FIGURE 3B shows six degrees of freedom (glenohumeral plus claviscapular joint systems), and FIGURE 3A shows nine degrees of freedom (glenohumeral, claviscapular, and sternoclavicular). At *A*, there is no one fixed joint center; note the range of movement of the humeral head. At *B*, the humeral head likewise shuttles about. Although it is less clear at *C*, there is, as will be shown later, likewise no fixed center. This illustration underscores the complexity of shoulder movements in a way that is not clear in globographic representations by Fick,[17] Braus,[7] and von Lanz and Wachsmuth.[38] Correct movements have been shown in this joint[5] by the use of *X*, *Y*, and *Z* coordinates.

The cadaver measurements referred to, although they have analytical value, are inadequate as representing living motions, and they are based on too few analyses. Measurements that have been made upon living subjects have likewise been inadequate for most joints, since they have ignored the contingent

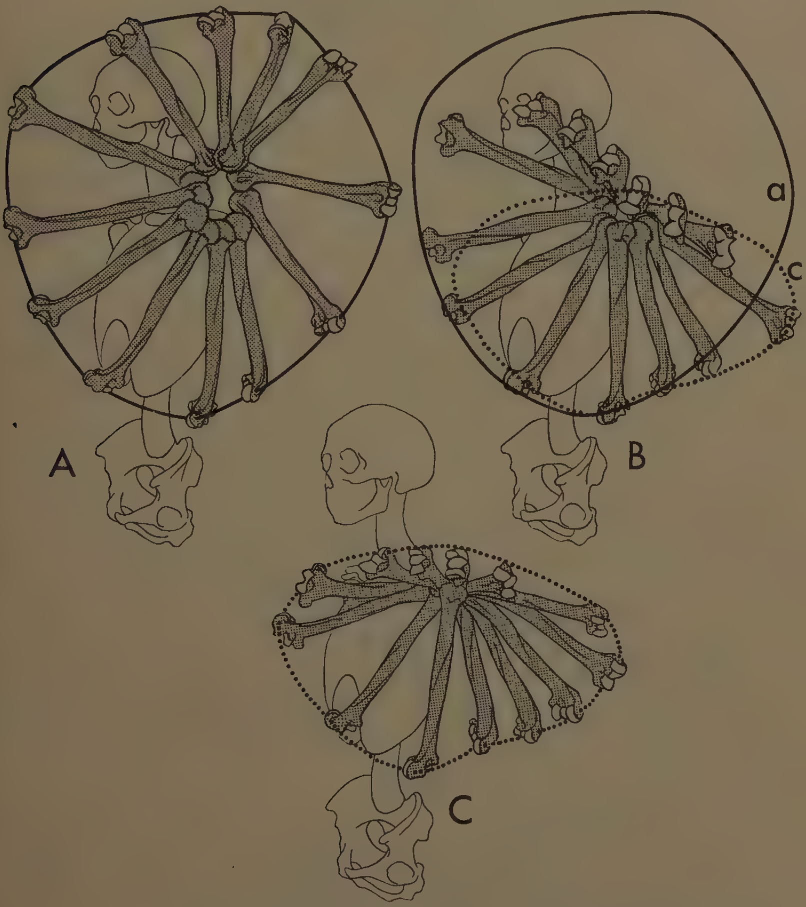

FIGURE 3. Range of humeral movement at the shoulder joints.

restraints and the complexity of component joint systems at certain regions (shoulder, foot, *etc.*). Muscular restraints also operate in the living subject. The fist, for instance, will not flex or extend at the wrist as much as the flat hand; the extent of hip bending is different if the knee is bent or straight.

There is a need for well-planned dynamic measurements of joint range (*i.e.*, link movement) on men, women, and children and on different racial and occupational groups. The effect of training and exercise should also be of interest.

### *The Relative Orientation of Adjacent Joints*

Although improved information on joint range is desirable, data on isolated joints cannot entirely reflect the cumulative geometric background for body motion. It is important to know, in addition, although the point has scarcely been recognized, the relative orientation of one joint to the next in sequence.

Measurements on bones have shown variability in the inclination and declination angles of the femoral neck relative to the femur when laid on a table with the posterior aspect of the condyles flat. The torsion angle of the humerus likewise has a variable range.[24] The plane of the tables of the tibial condyles lies at different angles to the shaft axis in different specimens; the plane of the scapular blade has a variable angle to a plane across the glenoid margin; the ulnar axis has a variable angulation to the axis of elbow bending; and the clavicular axis has a variable angulation to the plane of its acromial articular facet.

These points and others based on osteological material suggest that the bony span between the joints may be more or less twisted or turned relative to the joints. The excursion cones of one joint may face inward or outward or otherwise, relative to the excursion cone of the more proximal or more distal joints. Because of this, the cumulative range of the end member of a limb may have an orientation to the trunk in one individual that is quite different from that in another. An extreme example points to the problem; if a humeral twist directed the forearm backward or outward instead of forward and inward, how different the hand action would be. Again, how different the lower limb action would be if the knee were directed outward instead of forward. The variability in angulations of the joints at the two ends of a bone should cumulatively modify the motion patterns of different individuals. This is a field for the anthropometrist interested in dynamic problems.

### *Joint Centers in Relation to Links*

Until now, links have been regarded as axial core lines that intersect joint centers. The implication of the globographic technique is that joint centers are points or axes fixed relative to the bones. It will be shown here that joint centers have variable positions and that links in the body system do not have fixed lengths.

The German engineer, Reuleaux,[32] in 1875 developed a method for defining rotations in a plane in terms of instantaneous axes of rotation. The method has been applied to the jaw[3,9] and to the knee[39] in living subjects. FIGURE 4 shows the general method of Reuleaux. Two points in a body change their angular position as the body rotates from position *A* to position *B*. Lines drawn from the first to the second position of the two points are shown by a dashed and a solid line. Perpendiculars from the midpoints of each line intersect at point *AB*. This is the instantaneous center that defines the average (*i.e.*, circular) movement as the points change their angular positions. At a later moment, point *BC* defines a new instantaneous center for the movement *B* to *C*. In this way, a path of instantaneous centers corresponds with the whole rotation *A* to *E*. For a series of small angular displacements, the method gives an accurate picture of movements in a plane.

When one member of a joint preparation is rigidly fixed in a vise and the other is moved, two points on the latter change their angular relations in the same way as the points on the moving chip of FIGURE 4. Analyses of shoulder flexion and elbow flexion were combined in one illustration for FIGURE 5. For each 10 degrees of rotation of the humerus relative to the scapula (and for the ulna relative to the humerus), an instantaneous center has been shown by a black dot. In each instance, the joint centers formed a cluster of points that suggest erratic changes in axis positions with movement. Each of the other major limb joints shows comparable axis shiftings. Only truly reciprocal articular curvatures can be expected to slide about an axis of constant position. The diameter of the cluster was at least a half inch for the elbow (four specimens), and three-quarters inch for the shoulder (three specimens).[11] Clusters for shoulder adduction were of the same general size. The specific pattern differs from specimen to specimen, but the cluster sizes are comparable for each type of joint. It is possible that muscular actions in the living shoulder would move the contacting parts of the joint even more. The speed of action is believed to affect cluster size also.

If the link is to be defined as the spanning distance between the centers of rotation of adjacent joints, it must change its length, of course, from moment to moment in an unpredictable way. The humeral link may vary by one and one-fourth inches or more. Certainly, a dynamic anthropometry with such variability cannot hope for the millimeter or so tolerances sought in static anthropometry.

The wrist was analyzed for joint-center location by taking a series of X-ray views with angiocardiographic equipment. Fifteen exposures for a flexion or adduction sweep were made. (The forearm was supported well, and a projecting rod from a hand grip swept over a plane surface parallel to the film; tiny lead shot imbedded in the forearm support and in the moving rod represented static and moving points.) An analysis by the Reuleaux method of the superimposed images of the shot (the black dots) showed the familiar

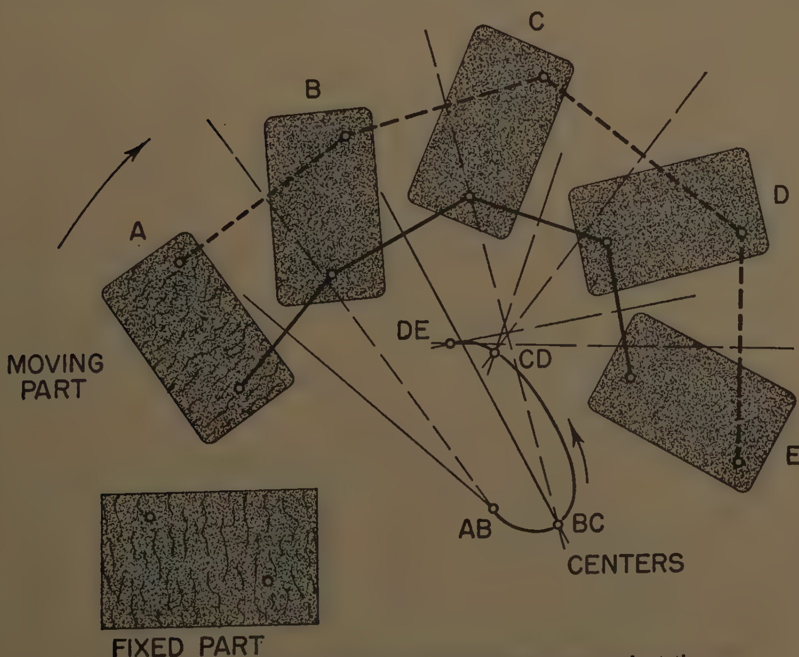

Figure 4. Reuleaux method of locating instantaneous centers of rotation.

cluster of instantaneous joint centers (white dots). They ranged over a three-quarter inch circle in the carpus and centered over the lunate-capitate junction. Similar procedures using motion-picture records with reference points traced frame by frame showed the same type of cluster.

With a cluster at the elbow and at the wrist, the forearm link, like that of the humerus, must vary in length from moment to moment. Analyses of movement must be content with mean link dimensions and mean joint centers with an inbuilt variablity factor.

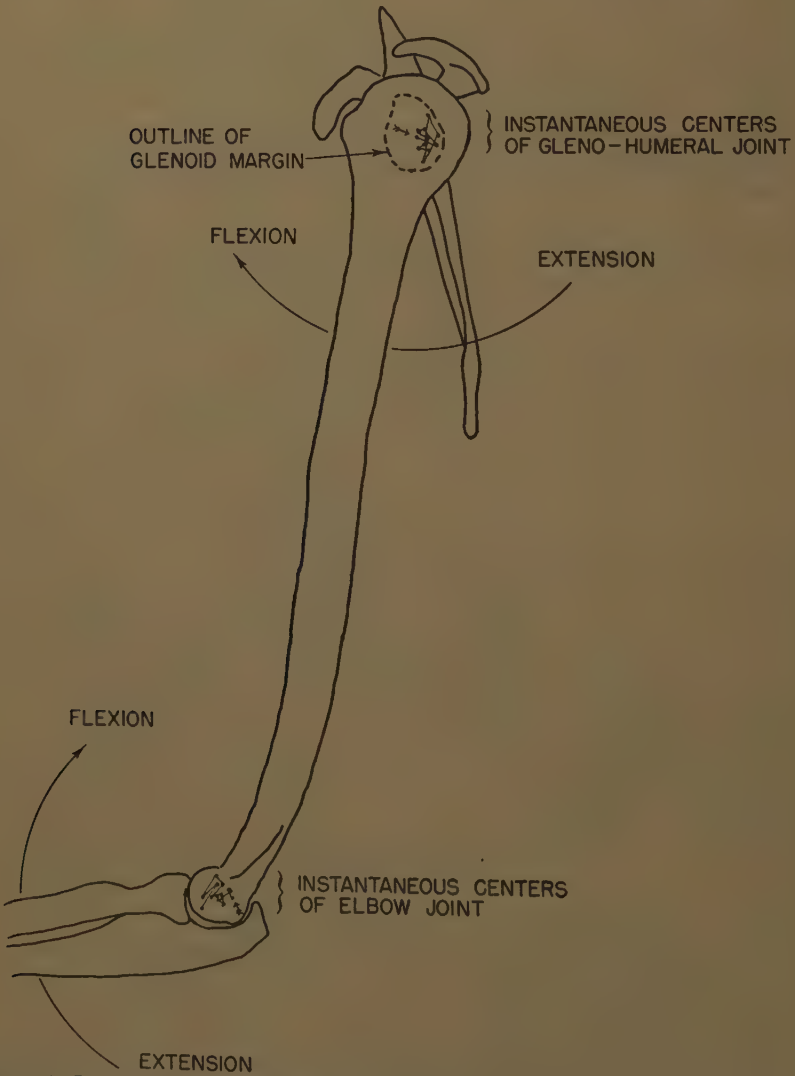
OUTLINE OF GLENOID MARGIN
INSTANTANEOUS CENTERS OF GLENO-HUMERAL JOINT
FLEXION
EXTENSION
FLEXION
INSTANTANEOUS CENTERS OF ELBOW JOINT
EXTENSION

FIGURE 5. Pattern of instantaneous joint center, for flexion-extension movements at the glenohumeral and elbow joints.

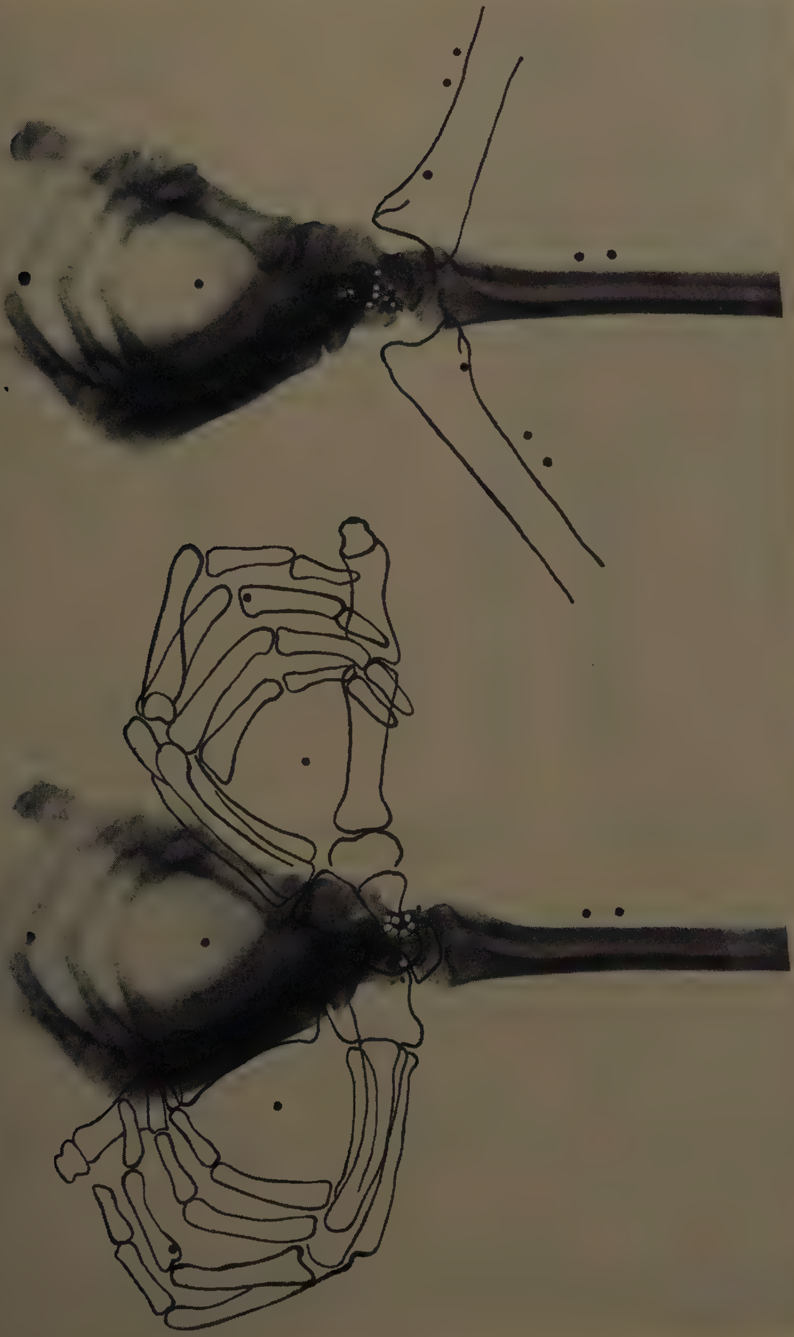

FIGURE 6. The pattern of instantaneous joint centers at the wrist joint.

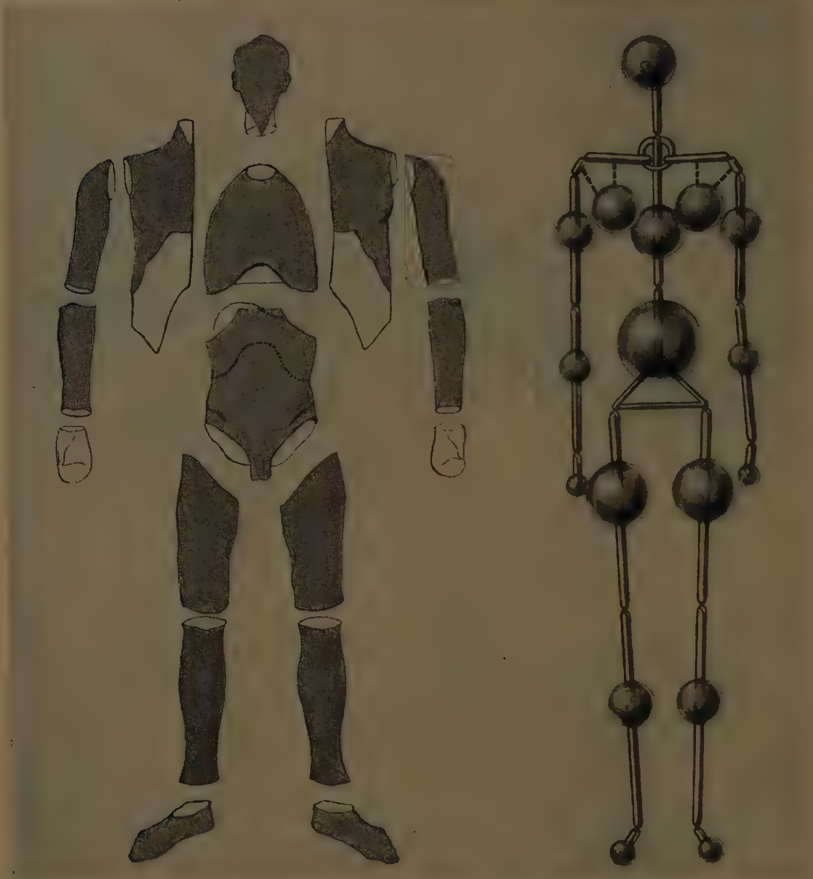

Figure 7. Plan of body dismemberment and relative masses of the body segments.

### *The Body Force System*

The foregoing account has been kinematic, *i.e.*, purely geometrical, and it has dealt with dimensions, types of movement, angles, orientations, and centers of rotation. But the body has mass. Eight cadavers have been dismembered[11] following the pattern of figure 7. If metal balls with a density of 8.0 (*cf.* steel, 7.8; brass, 8.4) were to be located on the links at the appropriate centers of gravity of body segments, their size would be about as shown. Younger individuals, or persons of different build, would vary from the pattern shown, but the figure is illustrative.

The centers of gravity for the arm, forearm, thigh, leg, and foot are located at points about 43 per cent along the proximodistal span of the segment length (*i.e.*, mean link length). This amounts to approximately three units from the proximal and four from the distal end. In the hand, the center is about 50 per cent of the distance from the wrist center to the end of the member for a mean position of rest, but it varies with hand posture. In the trunk, exclusive of the limbs but including the head, the over-all center of gravity lies about 40 per cent of the height above the hip joints. The head center of gravity is 43 per cent of the distance from the vertex to the disk between the seventh cervical and first thoracic segments.

Gravitational pull continually acts upon the segments, and the magnitude of the forces upon the parts is proportional to their mass. The mass imparts an inertia to the segments. Muscular force is required to hold a posture against gravity, to move parts if they are at rest, or to decelerate them if they are moving. The physics of rotation applies, and the parameters for a detailed mechanical analysis involve couples, a balancing of torques, moments of inertia, angular accelerations, angular momentum, and energy relations. The textbooks of physics and mechanics, however, are only partially helpful, since the relative motions of the segments depend also upon the kinematic system outlined above. Muscles, through their often-changing leverages, are an essential part of the forces acting on the body, but mass, inertia, and environmental forces are equally involved.

The technical analysis of certain dynamic problems may be reasonably outside the domain of dynamic anthropometry. Nevertheless, the influence of mass and other forces has a continuous effect upon the man who is subject to measurement. He develops a personal style in the handling of his body segments, he fatigues, he is saving on his energy, or he may be motivated toward unusual efforts. Psychological factors involving habit, training, boredom, motivation, and frustration may influence the quality and style of performance. In other words, the test subject is human and his handling of the postures and motions of his personal open-chain link system is individualistic. The vagaries of neuromuscular control make the body quite unlike the closed-chain system of machinery.

### *Measuring the Dynamic Individual*

Three general classes of dynamic measurement may be anticipated and the purposes of the measurement are pertinent:

(1) Any specific skilled individual performance or critical phase of such performance may be measured as an approach to understanding the mechanical nature of the activity. The individual is secondary to the specific performance. This emphasis prevails in locomotion studies, in the analysis of top-level athletic performance, in the investigation of the use of prostheses by the maimed, and in the study of skilled repetitive behavior of the sort used in industry. Perhaps measurements made with such aims are not strictly anthropometric.

(2) The defining of the over-all or potential space used by representative individuals of a population may be measured. The potential range of effective hand or foot postures may be analyzed for seated, standing, or recumbent postures, and the relative effectiveness of the different regions within reach may be compared.

(3) The variability in the dimensions, style, and performance exhibited by samples of a population may also be measured so that knowledge of the general pattern of certain purposeful operations may be known. For instance, it

should be possible to analyze the general kinematic activity and space requirements of typists, desk workers, punch press operators, or the drivers of vehicles.

### *Characteristics of the Skilled or Repetitive Performance*

When actions are studied from motion picture records analyzed frame by frame or from stroboscopic records, the motions are broken into a series of instantaneous stages. Students of locomotion (Bernstein,[4] Elftman,[15, 16] Eberhart and Inman,[13] Klopsteg and Wilson,[23]) and analysts of the sports patterns and other activities[10, 14] have worked with this technique. Simultaneous or accessory records from the side, front, rear, and above or below have advantages in this work.

FIGURE 8 shows a representative type of record that might be analyzed in this fashion; it shows an athlete putting the shot. The record shows rhythm, sequence of postures, and a pattern of force application directed solely to the twin objectives (1) of getting a maximum distance of throw, *i.e.*, the highest possible velocity at the moment of release for the best possible trajectory; and (2) enough body control in the follow-through phase for the performer to stay within the prescribed ring. An alternate and more carefully worked out link figure analysis would have permitted measurements of both velocity and acceleration of the travel of the shot and the angular velocities and accelerations of

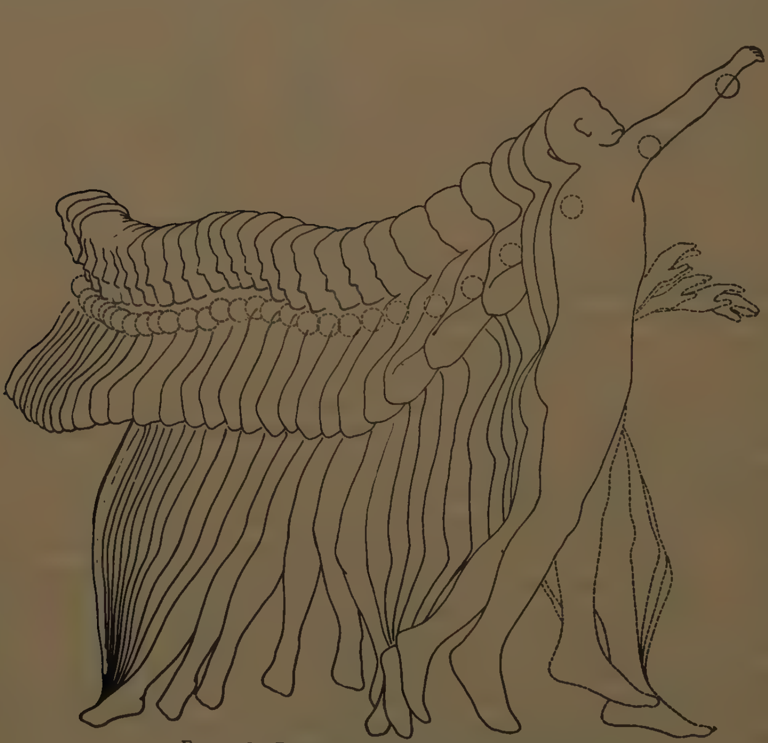

FIGURE 8. Pattern of body movement in the shot put.

the motions of the body segments. Knowledge of the moments of inertia of the body segments would contribute further to the analysis. The relative value of the fall forward, the hop, and the lunge may be stated in quantitative terms. Top-grade performance may be analyzed in comparison with throws of less distance. The strongest and the weakest phases of the performance may be contrasted, and methods for improvement may be devised.

Any critical performance is subject to this type of analysis when quantitative parameters are available. The capacity of a prosthesis-wearing amputee may be studied, and the effectiveness of tool using may be analyzed. The purpose and emphasis of the analyst will ordinarily be a search for an understanding of the factors that operate in the performance.

### *Work-Space Problems*

Quite in contrast, the development of effective work spaces, which do not cramp large individuals nor inconvenience others by poor placement of controls, calls for studies that relate to a poplulation. The hand and foot are specialized as the utility agents of the limbs. For any position of the body, the effective reach of these parts defines the space available for potential activity. It would appear feasible, at first sight, to determine such a range of hand or foot movements with a reasonable accuracy if the link dimensions and amplitude of joint movements were known. It should be expected that the range of rotational movements at each joint in a chain of links could be combined in sequence. FIGURE 9, *A* and *B*, points to the impracticability of such a procedure, however.

Assume that the humerus moves in the plane of the paper through an arc such as that shown at *A*. Then assume, further, that the elbow has a flexion-extension range of 140° and that the hand is outstretched. The sketch at *B*, which represents a compass construction based on the upper-limb link dimensions of TABLE 1, shows the range of movement of both the wrist center and the finger tips. The construction ignores the space medial or lateral to the plane of the analysis. It would be difficult to compare the ranges of different individuals, and one may doubt if given test subjects would really approximate the range as estimated.

A way out of the difficulty is suggested by the lower sketches of the figure. At *C*, a terminal point on the humerus describes an arc as the link moves in a plane about its joint center. At *D*, a point on the forearm shows both rotatory and translatory movements in the plane of the paper. If a third link (hand) is attached to the moving part and is held in a constant orientation, it too executes translatory movements as well as rotatory. For additional links (fingers), translatory movements are likewise possible relative to the trunk. More generally, in a chain of three or more links in any plane, that link which has two joints allowing compensatory movement may have translatory motion as well as rotational movement.

Both the hand and foot form such a relation to the trunk, hence motions of either end member may be measured as translatory movement in given test subjects and the ranges of movement may be grouped or compared. FIGURE 10 shows a method for analyzing the range of hand movement relative to some

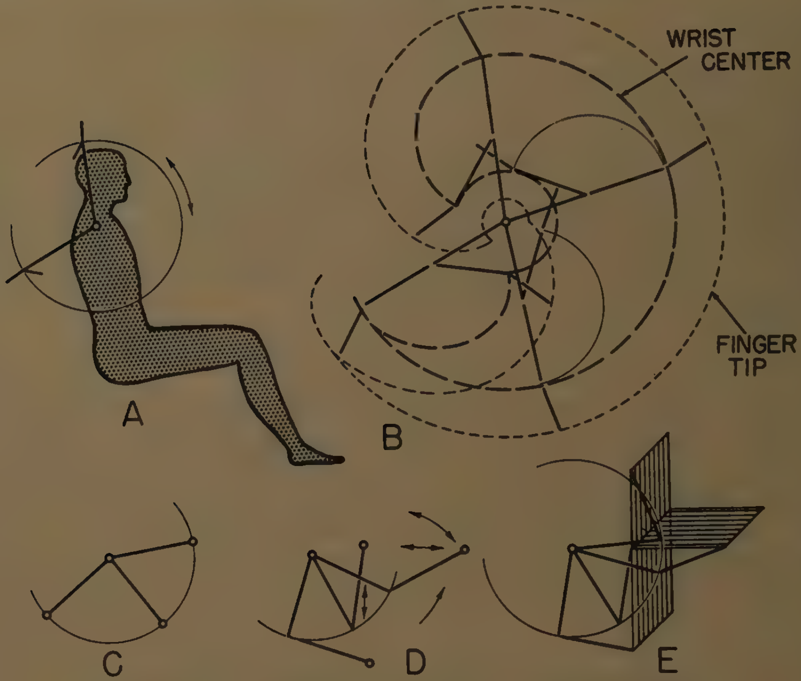

FIGURE 9. Compass construction showing movements of upper limb links.

TABLE 1

LIMB-BONE LENGTHS AND ESTIMATED LINK DIMENSIONS FOR A MALE BUILD OF 175 CM. (5′9″) STATURE

| | Bone Length | Link Length |
|---|---|---|
| | *cm.* | *cm.* |
| Clavicle | 16.3 | 14.1 |
| Scapula | | ±3.5 |
| Humerus | 33.9 | 30.2 |
| Radius | 25.4 | 27.2 |
| Hand (outstretched) | 19.0 | 7.0 to C.G. |
| Femur | 47.5 | 43.4 |
| Tibia | 37.2 | 40.9 |
| Foot (heel to toe) | 26.7 | 8.2 to C.G. |

fixed reference point on the seat on which a subject sits. The subject holds a reference grid with the hand continually in a fixed orientation—prone, supine, grip vertical, *etc.*—and he moves the hand and grid over a plane surface, such as a wall, to the limits allowed by the cumulative joint action of the limb. In the method shown, a flashing neon glow lamp at the hand describes a path that represents the limits of extreme motion in the plane of reference (other moving lights at the elbow and shoulder are irrelevant to the central problem). The 45° mirror view simply provides a check that the movement is reasonably in the plane of reference.

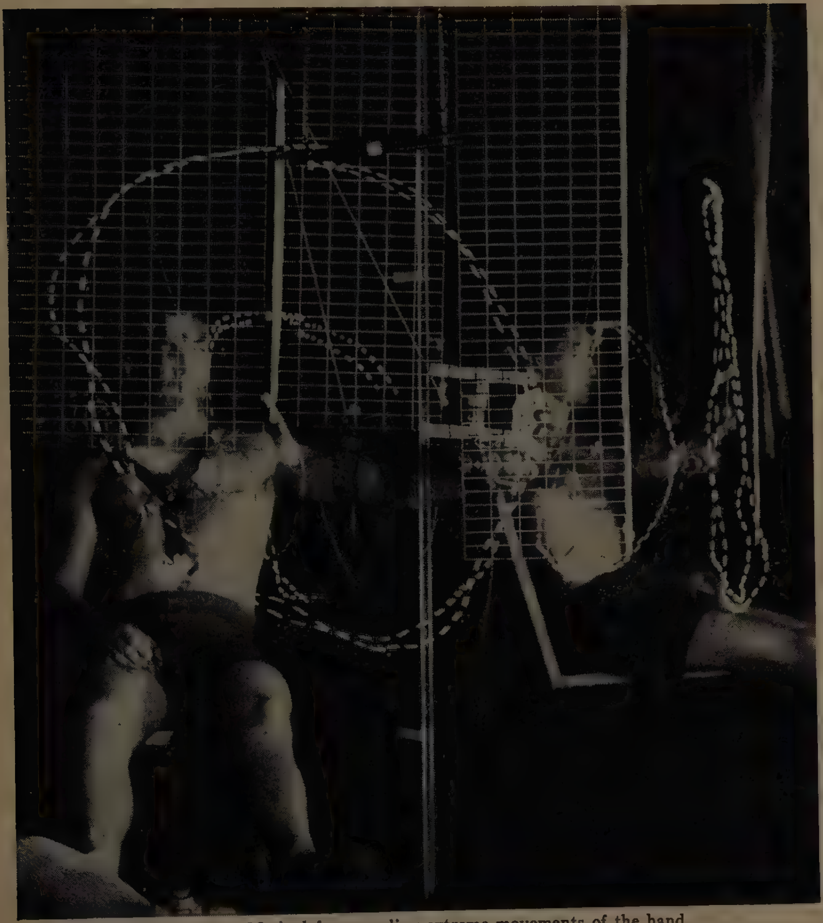

FIGURE 10. Method for recording extreme movements of the hand.

When the subject (and the seat) is moved forward a measured distance, a new record shows the range in a plane closer to the subject. Enlarged tracings of successive records, when superimposed, appear as in FIGURE 11; a reconstruction of successive records may be presented also as a three-dimensional model (FIGURE 12). The surface of the shape represents the limits of reach relative to a fixed reference point (on the seat) for the hand as held in a fixed orientation. The term "kinetosphere" has been coined for the space required by an end member (hand or foot) held in a constant orientation and moving in translation relative to some fixed reference point.[11]

Records (such as those shown in FIGURE 11) representing sections through a kinetosphere can be compared for different subjects. The centroid position may be calculated, and the volume may be determined from planimeter measurements of the several outlines. Perpendicular sections through the centroid in different planes (horizontal, sagittal, or transverse) may be scaled off on coordinate paper. These likewise may be compared directly for different end member orientations or for different individuals. Records of different individuals may be superimposed, traced, and averaged. Deviations from the average in different directions may be measured.

When the arbitrary fixed hand orientation is changed, certain limiting ligaments at one or more of the joints bind in such a way as to change the cumulative space range. Accordingly, the shape envelope differs with each hand orientation. Records of different hand orientations may be grouped in different combinations.

The kinetosphere analysis forms a valuable tool for defining the range of actual motion exhibited by subjects. The common region for all hand orientations may be defined. In contrast, regions for only special hand orientations may be located. The length of straight-line movements in any direction may be determined. The amount of right-left hand overlap may be measured for various hand orientations. Regions (centroids) that are, on the average, farthest from the limiting boundary may be located. Thus, in addition to learning the limits of reach for various hand orientations, it is possible to evaluate the space in terms of regions of variable utility to the body.

The empirical subject-by-subject study of kinetospheres is not a purely dimensional study. It deals with actual rather than ideal movements of subjects.

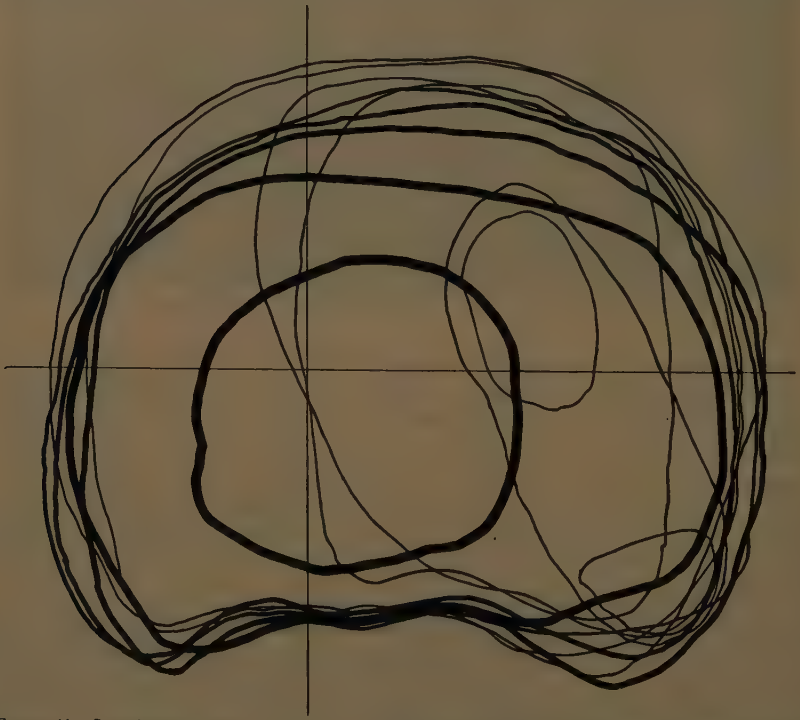

FIGURE 11. Superimposed frontal-plane serial sections showing the pattern of extreme movements of the prone hand.

Any psychological factors, such as laziness, willingness to exert to the limit, and individual limitations associated with peculiarities of the joint range and limitations due to fat or muscular restraint are to be found in the records much as they will be in actual purposeful movements within the reach of the different subjects.

Cumulative records of kinetospheres on one subject or of composites representing a group of subjects may be measured. Average volumes or linear dimensions may be determined for the space within reach. Applications to both the foot and the hand have been studied.[11]

### *Variability in Purposeful Behavior*

Human activity involving tools, furniture, and equipment may be broken down for analysis into a variety of purposeful patterns—the pianist, the or-

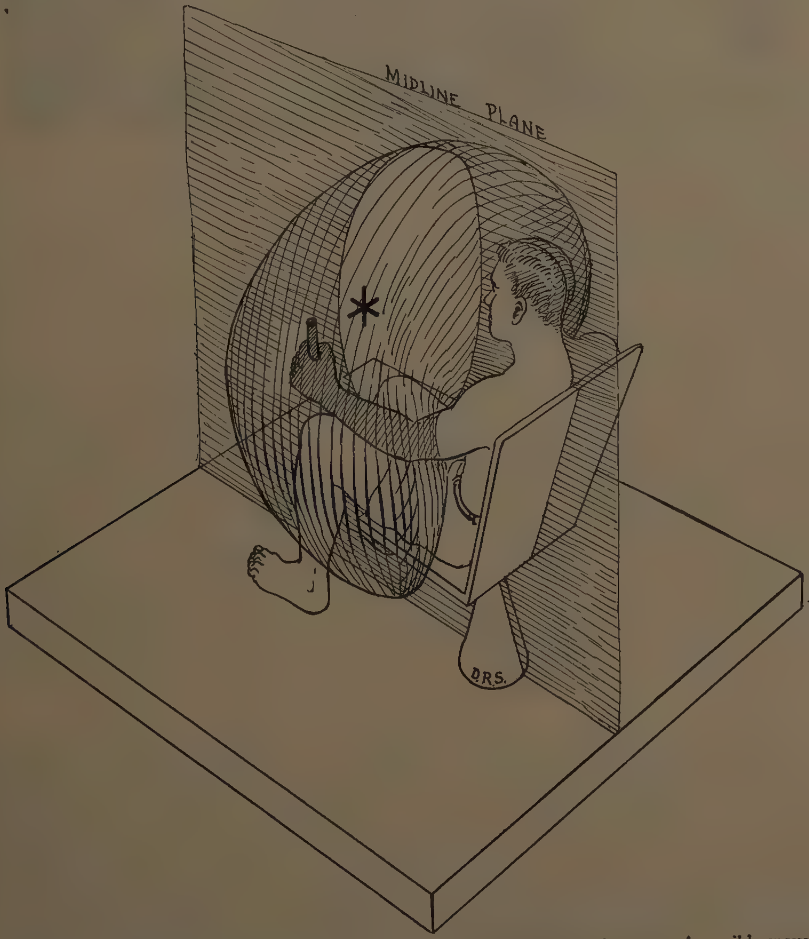

FIGURE 12. Sketch of a 3-dimensional model of a kinetosphere showing the range of possible movement of the hand when held with the grip vertical.

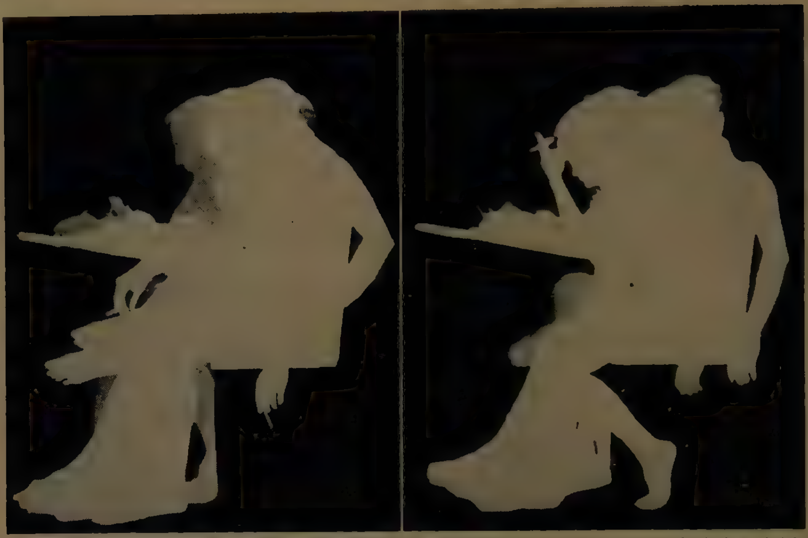

FIGURE 13. Representative phases of body posture of two subjects performing comparable desk activities.

ganist, the desk worker, the typist, the cook, the driver or passenger of a vehicle, or the operator of a machine in industry. The body patterns of such individuals may be recorded for representative phases of this activity, such as the multiple exposure records of FIGURE 13 showing reading, writing, and other desk activities. Permanent records of this type may either show equal time intervals—say minute intervals—or they might be selective and show merely representative phases of a total action pattern. Such records show individual differences in the style and pattern of people accommodating their dimensions and mass to the tools and purposes of the activity. Records might be made in different planes, and different individuals or classes of activity might be compared. In any event, the records may be measured in terms of linear dimensions, areas, or volumes. Such measurements should pertain to furniture designing or architectural usage.

What is pertinent is that the actual variety of postures and movements be objectively studied rather than imagined. If a record of actual body patterns is available, methods for significant measurement can be devised.

### *The Study Sample for Measurement*

It should be obvious that where the nature of a repetitive stereotyped activity—walking, running, athletic performance, *etc.*—is to be studied, one should select individual representative or top-level performers. Population measurements are unimportant here. Population data are likewise unimportant if applications are to be made for one subject, or for a group of individuals of similar dimensions. There should be no problem in planning work-space facilities for a given body size. In the practical use of sizing data, a limited range of body dimensions can be fitted well, *viz.*, clothing, furniture, workspace, but as the range of individual dimensions approaches that of a large population, the fit becomes less and less good.

The vehicle driver or the industrial worker who must be fitted with standard equipment, however, represents a large population that can be measured—even by static anthropometry—only through samples. This means that the dimensions of the extreme deviates in the total population cannot even be predicted. The mean, however, may be estimated with reasonable accuracy, and it is equally possible to designate individuals who would be included within plus or minus 1, 2, or 3 standard deviations, or individuals within certain percentile ranges.

Accordingly, one follows the principle of the greatest good for the greatest number. If a work space fits, for example, 90 per cent of a population reasonably well, 10 per cent (*i.e.*, the largest and smallest) are inconvenienced to some degree, and they must compensate as best they may. No one in specific instances can define the critical percentile with assurance, but 90 to 95 per cent are reasonable tentative levels.

The labor involved in dynamic measurements precludes studies on large population groups. When a population of interest, or a reasonable equivalent, has been measured by static anthropometry, the mean values and the ±2 (or ±3) standard deviation level should be available. These limiting values or calculations of the 95th and 5th percentiles (including 90 per cent of the population) define individuals of critical larger and smaller dimensions. If, now, small test samples of individuals are carefully selected, with reasonable concern for tolerance limits in several dimensions (height, weight, limb dimensions, *etc.*) these should be fair subjects for dynamic studies. Dynamic data on samples of even 5 or 10 large, median, and small subjects, selected on the basis of static measurement should form a fair functional approximation to what would be shown by the larger group.

For each of the dynamic study groups, the performance range would vary with differences in joint movement, strength, willingness to exert, *etc.*, as in any practical situation. Subjects of small dimension might well exceed the range of performance of some individuals in both the other groups. This approach allows the defining of average, superior, and restricted levels of performance that would be representative for the larger population. The use of highly selected groups should have pertinence in both the study of potential ranges of movement, *i.e.*, work-space data, or in the study of special purposeful patterns of behavior involving furniture, tools, and other accouterments.

## *Conclusions*

If a dynamic anthropometry relating to movement patterns is to be developed, it must proceed on an understanding of the nature of body kinematics and the importance of forces in relation to posture and movement. The actual movements must be studied and recorded, preferably with adequate permanent records of the motions; the purposes of the study will determine the parameters for measurement. The anthropometry may fairly relate to but one individual rather than to a population; alternately, the data may have significance only in relation to a population group. In the latter instance, it would appear preferable, rather than to use a random group of study subjects, to select test subjects carefully, so that they match definite dimensions in the population to which the data are to be applied. The over-all potential range of motion can be defined, or a purposeful class of behavior may be measured, when carefully selected representative individuals are studied in actual or well-designed mock situations. Static measurements made with subjects in one posture cannot be reassembled to represent dynamic patterns. Static measurements, however, do have importance in the defining of a population for which dynamic measurements may have pertinence. They likewise provide a basis for the judicious selection of study subjects for dynamic measurements.

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# STUDIES IN HUMAN BIOMECHANICS*

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## *Introduction*

Biochemics is the study and analysis of those phenomena of living bodies that are essentially mechanical in nature. The techniques and terminology used in such studies are those employed by engineers for analyzing similar phenomena in engineering structures and materials. Consequently, some familiarity with certain principles of mechanics is essential.

One of the most basic concepts in mechanics is that of *force*, which is most simply defined as a push or a pull. There are three principal kinds of force that are identified by the effect they produce on the body to which they are applied. A force (FIGURE 1a), tending to push the body together, is a *compressive* or compression force, while one tending to pull the body apart is a *tensile* or tension force. If the force tends to cause immediately adjacent parts of the body to slide in opposite directions on one another, it is a *shearing* or shear force.

Application of a force to a body creates strains and stresses within the body. *Strain* (FIGURE 1c) is the proportionality between the original dimensions of a body and its dimensions after a force is applied to it. The type of strain produced in the body is the same as that of the force causing it. For example, if a rubber band one inch long is streched to three inches in length, it has undergone a tensile strain of two.

The strain occurring in a body to which a force has been applied is accompanied by a corresponding *stress* (FIGURE 1b), which is the resistance within the material of the body to the deforming action of the force. If the strain is large enough, it can be seen, but stress can be computed only in terms of load per unit area (lbs./in.$^2$ or kg./mm.$^2$). The value obtained for stress is commonly used as synonymous with the *strength* of the object or material.

Plotting stress against strain gives a *stress-strain curve* whose slope and shape show the mutual relations of these two phenomena during loading of the body or material. The curve is also used in determining the *modulus of elasticity* or stiffness of material. The energy the body absorbed to failure is indicated by the area of the region beneath the stress-strain curve.

When a force is applied to a body, it causes it to deform or change its shape and dimensions, the magnitude of the deformation depending on the size of the force. In most bodies, the deformation is not permanent, unless breaking occurs, and the body returns to its original dimensions when the force or load is removed. Such bodies are said to be *elastic*, and the *elastic limit* of the body is the point beyond which the body does not return to its original dimensions when the force is removed. Few bodies or materials, however, are perfectly elastic.

Most of the bones of the body, especially those of the limbs, are subjected to a bending action by such factors as gravity, support of body weight, and mus-

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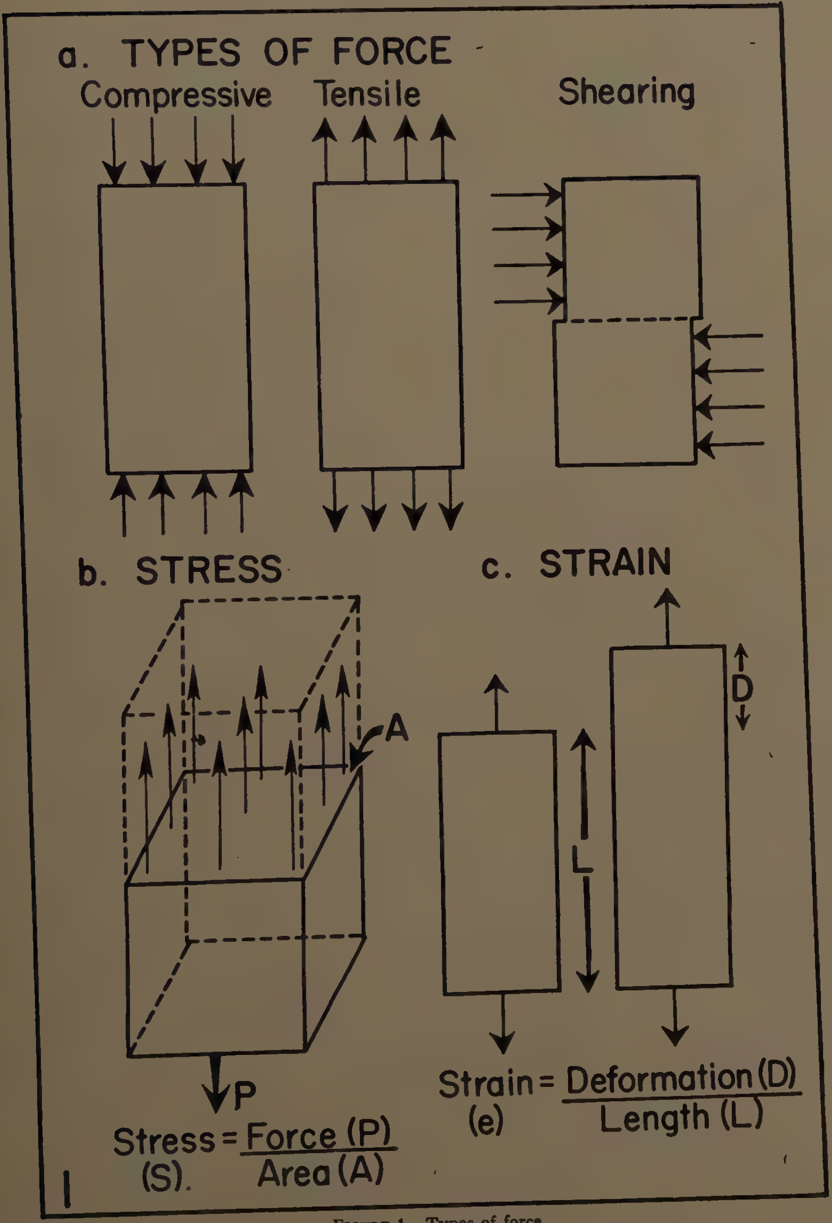


FIGURE 1. Types of force.

cular activity. The bending creates tensile strains and stresses on the convex aspect and compressive strains and stresses on the concave aspect of the bent bone. These principles are illustrated by the behavior of a column under different types of loading.

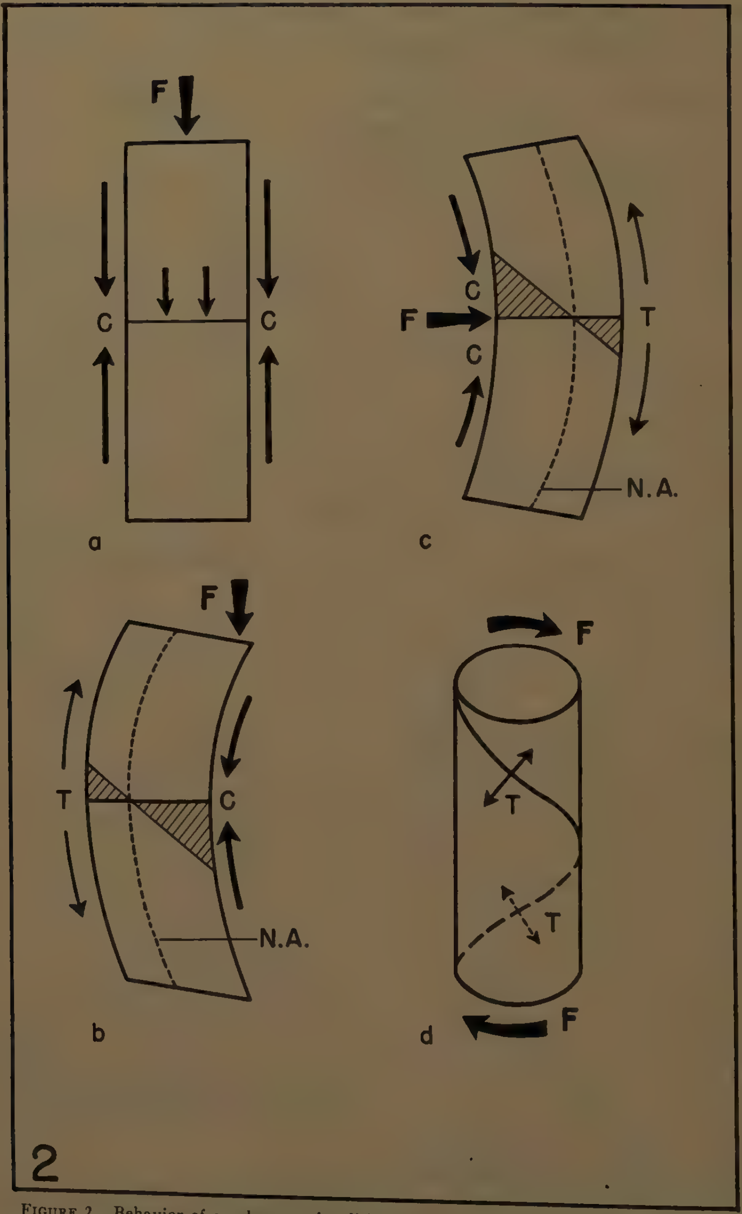


FIGURE 2. Behavior of a column under different types of loading (after Evans, 1952).

A column to which the force (F) or load is concentrically applied (FIGURE 2a) is subjected to compressive stress and strain (C) throughout its cross section area, but an eccentrically loaded column (FIGURE 2b) or one loaded perpendicular to its long axis (FIGURE 2c) is bent. As a result of this bending action, tensile stresses and strains (T) are developed on the convex aspect of the bent column, while the opposite concave side is subjected to compressive stresses and strains (C). The magnitude of these strains and stresses is greatest at the surface of the column and decreases internally until they are zero. The plane at which the forces are zero is called the neutral axis (N.A.). When a column is subjected to a torsion or twisting force (FIGURE 2d) it gives rise to tensile strain (T) which takes a spiral course around the column at approximately a 45° angle to its long axis.

The biomechanical behavior of intact bones has been studied by several methods, recently reviewed by Evans (1953), but only two of them, Stresscoat and the strain gage-oscilloscope method, have been used on bones of living animals. Consequently, the results obtained by these two methods give a truer picture of the mechanical behavior of living bones. For this reason, the present discussion will be restricted to studies in which stresscoat and the strain gage-oscilloscope techniques were employed.

"Stresscoat" is the trade name for a brittle resinous lacquer originally developed for locating sites of tensile strain and failure in aircraft structures (de Forest and Ellis, 1940) and now used extensively for similar purposes in other industries. The lacquer cracks in response to tensile strain occurring in the material upon which it has been sprayed, the site of the first cracks indicating the area of greatest tensile strain where failure will occur with sufficient load. The orientation of the cracks is transverse to the direction of the tensile strain in the underlying material. The individual cracks are quite fine and, in order to see them more clearly, the Stresscoated object can be sprayed with white statiflux powder. In spraying, the powder is given an electrostatic charge so that it lines up along the cracks and makes them more visible. The statiflux powder does not change the sensitivity of the lacquer and, if no tensile strain pattern is obtained with the first test, another can be made without reapplying the stresscoat.

The sensitivity of the Stresscoat lacquer is calibrated in inches/inch, *e.g.*, a lacquer with a sensitivity of 0.0006 inches/inch means that, every time an inch of the material upon which the lacquer has been sprayed is stretched 0.0006 of an inch, the overlying lacquer will crack. The magnitude of the apparent tensile stress (lb./in.$^2$) produced in the object being tested can be computed by multiplying the tensile strain (indicated by the sensitivity of the Stresscoat lacquer) by the modulus of elasticity of the material composing the object. "Stresscoat" is really a misnomer, because the pattern obtained is actually a strain, not a stress, pattern. Generally, the cracks constituting a strain pattern are traced with India ink for photographic purposes.

### *Biomechanical Behavior of the Skull*

The Stresscoat technique was first applied to a study of the biomechanical behavior of bones by Gurdjian and Lissner (1945), who have used it in a classical series of studies on skull deformations and fractures. One of the first questions these investigators considered was how closely stresscoat patterns in dry bones resemble those which would occur in living bones under similar condi-

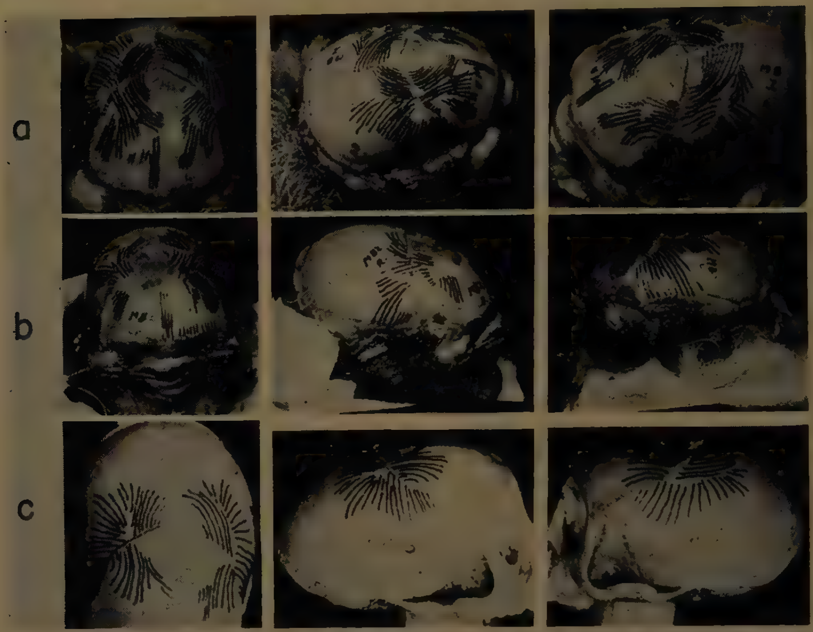


FIGURE 3. "Stresscoat" patterns in the skull of a monkey. See text for explanation (after Gurdjian and Lissner, 1945).

tions. This was answered by a series of experiments on the skull of dogs and macaque monkeys (FIGURE 3).

In their first experiment, the scalp of the living anesthetized animal was reflected, the exposed bones Stresscoated, and then a blow applied to the skull. The Stresscoat pattern obtained was traced with India ink and photographed (FIGURE 3a). The second experiment (FIGURE 3b) was a repetition of the first on the skull of the dead animal. The skull was then cleaned, dried, and the experiment repeated a third time (FIGURE 3c). The Stresscoat patterns obtained in the three experiments were very similar regardless of the experimental conditions. The only essential difference noted was that the patterns were somewhat more extensive in the skull of the living animal than those in the dead animal or the dried skull. It was, therefore, concluded that Stresscoat patterns produced in dry bones can safely be used for analyzing the biomechanical behavior of living bones.

The skull is not normally subjected to bending action, because it is not a weight-supporting structure and, with the possible exception of the muscles of mastication and those attached to the occiput, is not acted upon by powerful muscles. However, Gurdjian, Webster, and Lissner (1950a), in discussing the mechanism of skull fracture, point out that bending occurs when a blow is applied to the skull. Thus (FIGURE 4), there is inbending of the outer aspect of the skull at the site of impact, accompanied by outbending at some distance from the point of impact. This behavior is beautifully demonstrated by Stresscoat patterns Gurdjian, Webster, and Lissner (1947) obtained on both the outer

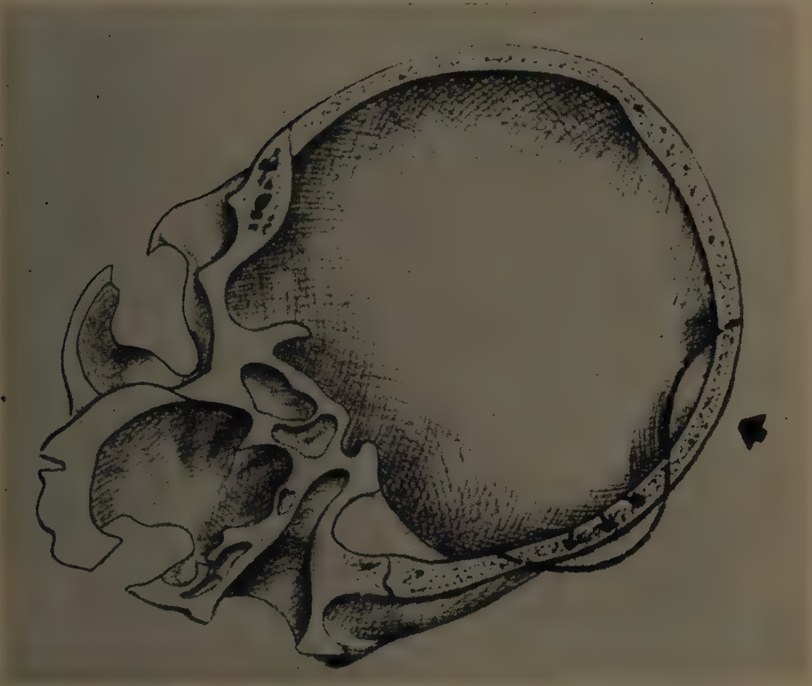


FIGURE 4. Behavior of the skull under impact (after Gurdjian, Webster, and Lissner, 1949).

and inner aspect of the skull. The inbending of the outer surface of the skull gave rise to a well-developed stellate deformation pattern on the inner aspect of the skull opposite the site of impact (FIGURE 5a). The accompanying outbending of the bone produced another deformation pattern on the outer aspect of the skull at a distance from the site of impact (FIGURE 5b). The deformation pattern on the inner aspect of the skull was the result of circular tensile strain, while that on the outer aspect of the skull indicated side to side (superior and inferior group of cracks) and anteroposterior strain (lateral groups of cracks). Examination of the deformation patterns in the monkey skulls (FIGURE 3) shows that both circular and radial tensile strain occurred in the outer aspect of the skull. The radial strain produced the circularly oriented cracks, while the radially oriented cracks arose from circular strain.

Gurdjian, Webster, and Lissner (1950a) were also able to demonstrate areas of different stress level. Thus, the first or weakest level (FIGURE 6, 1), following a posterior parietal blow, was in the temporal region. The next weakest area (FIGURE 6, 2) was in the superior parietal region, while the parieto-mastoid region (FIGURE 6, 3) was the strongest or the region of tertiary stress level. Experimentally produced single, double, and triradiate linear fractures in cadaver heads (FIGURE 7) corresponded to these three stress levels, and indicated the fractures arose from failure of the bone from the tensile stresses within it. The Stresscoat patterns produced by loading different areas of the skull enabled them

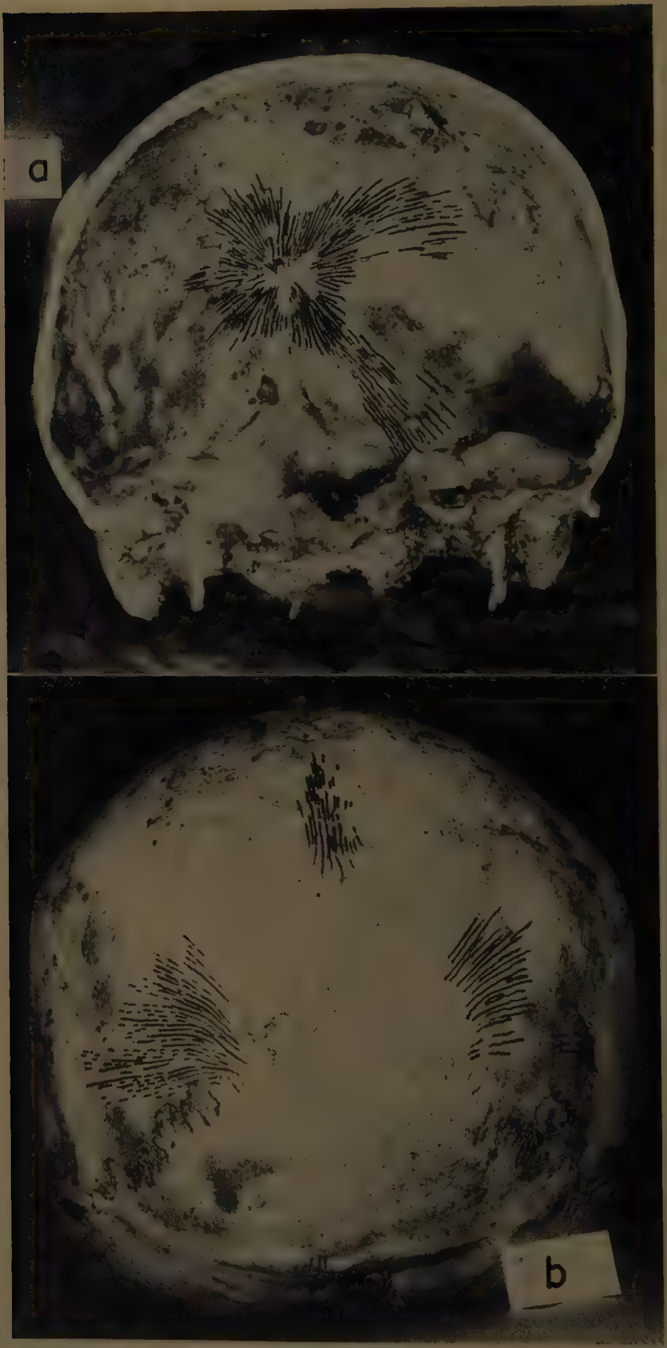


FIGURE 5. "Stresscoat" patterns on the inner (a) and outer (b) aspects of a human skull (after Gurdjian, Lissner, and Webster, 1947).

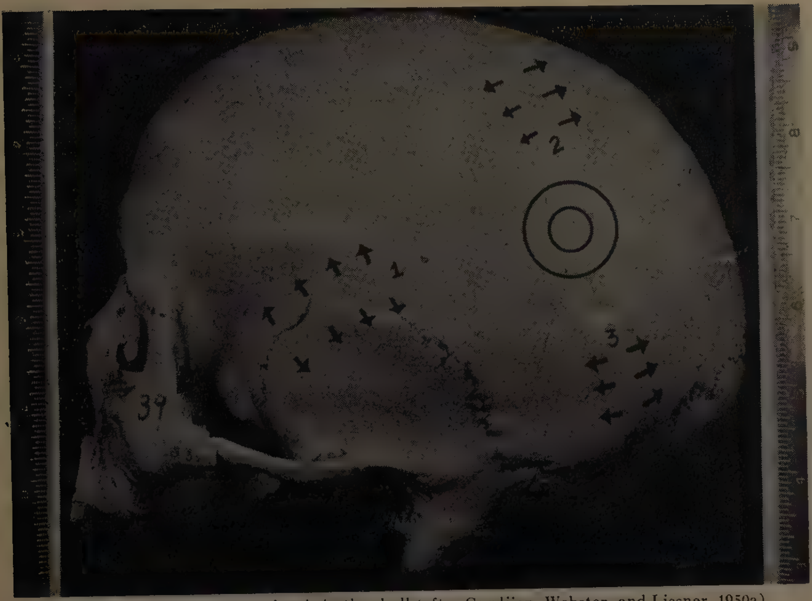


FIGURE 6. Different stress levels in the skull (after Gurdjian, Webster, and Lissner, 1950a).

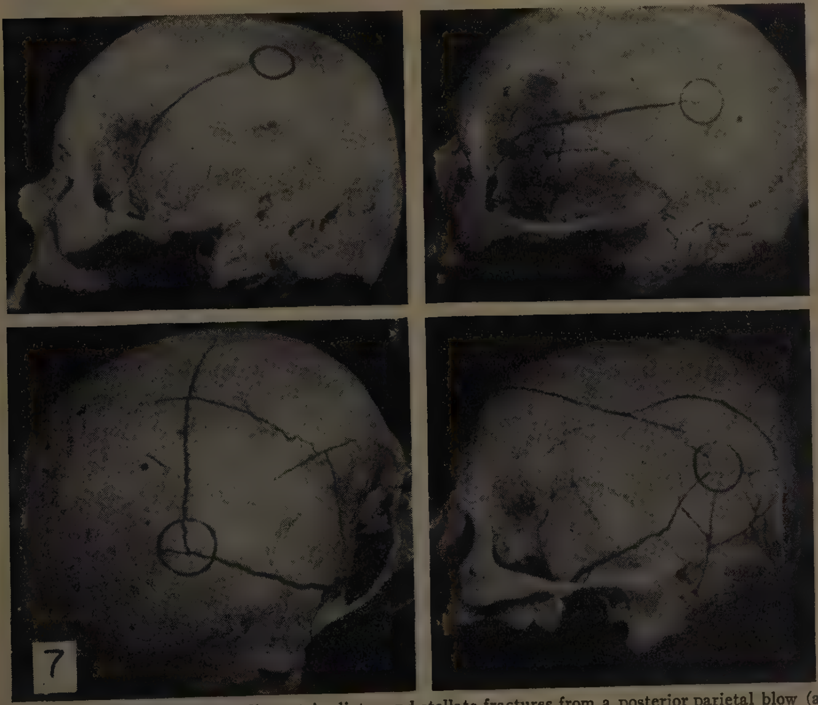


FIGURE 7. Monoradiate, biradiate, triradiate, and stellate fractures from a posterior parietal blow (after Gurdjian, Webster, and Lissner, 1950a).

to predict with a high degree of accuracy where a fracture would occur if the site of the blow were known. They (1950b) verified this by comparison of experimentally produced Stresscoat patterns with actual fractures seen in the clinic (FIGURE 8).

By means of the strain gage-oscilloscope method, Gurdjian, Webster, and Lissner (1950a) measured the time required for the skull to deform and fracture. The oscilloscopic record (FIGURE 9a) showed that 0.0006 of a second elapsed from the time of impact on the scalp to the beginning of deformation of the skull. This was followed by another 0.0006 second until fracture occurred. The latter event opened the circuit, since the fracture passed through the strain gage cemented on the skull (FIGURE 9b).

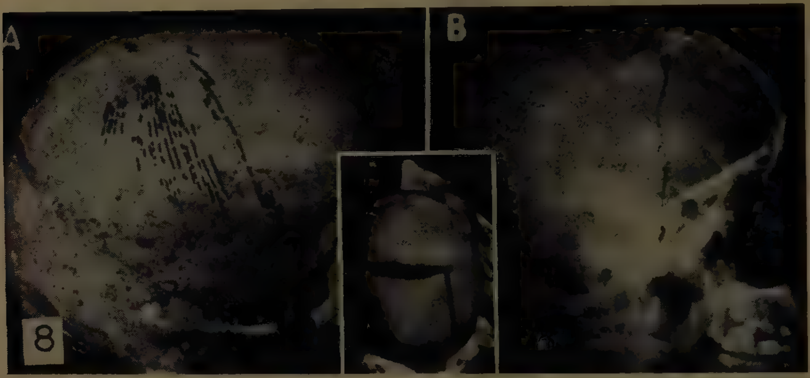
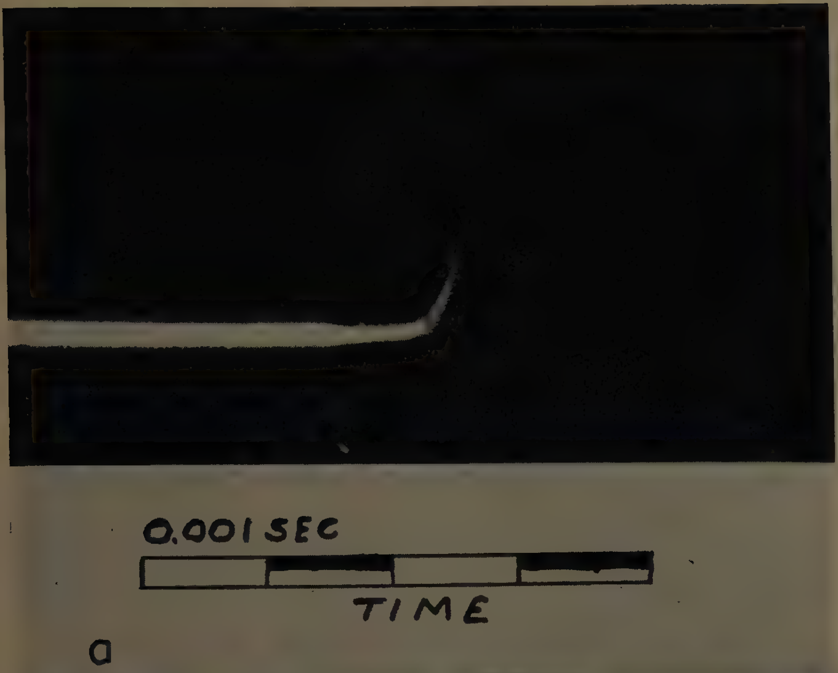


FIGURE 8. Comparison of stresscoat pattern with a clinical fracture (after Gurdjian, Webster, and Lissner. 1950b).

### *The Biomechanical Behavior of the Femur*

The Stresscoat technique has also been used in studying the biomechanical behavior of the femur in different orientations and under various conditions of loading. Stresscoated bones were studied under static loading in a materials testing machine calibrated to an accuracy of ±1 per cent. Similar bones were subjected to dynamic loading by resting the bone, or a part of it, upon a 160 lb. steel slab and dropping a 7.9 lb. brass block upon various parts of the bone. The brass block was caught by hand on the rebound so that it struck the bone just once. The weight of the block multiplied by the distance through which it was dropped gave the inch pounds of energy applied to the bone. Because of the relatively small amounts of energy used in the tests it was assumed that all of it was expended in deforming the bone since the amount of energy absorbed by the steel and brass blocks would be negligible.

That the behavior of the femur was like that of an elastic body was easily demonstrated (Evans and Lissner, 1948) by static vertical loading of the bone. In the unloaded bone (FIGURE 10a), a white thread extending vertically from the most medial point on the head of the bone to the shaft was taut. However, under a load of 650 lbs. (FIGURE 10b), the thread was slack. On removal of the load, the thread again became taut, indicating that the bone returned to its previous condition.



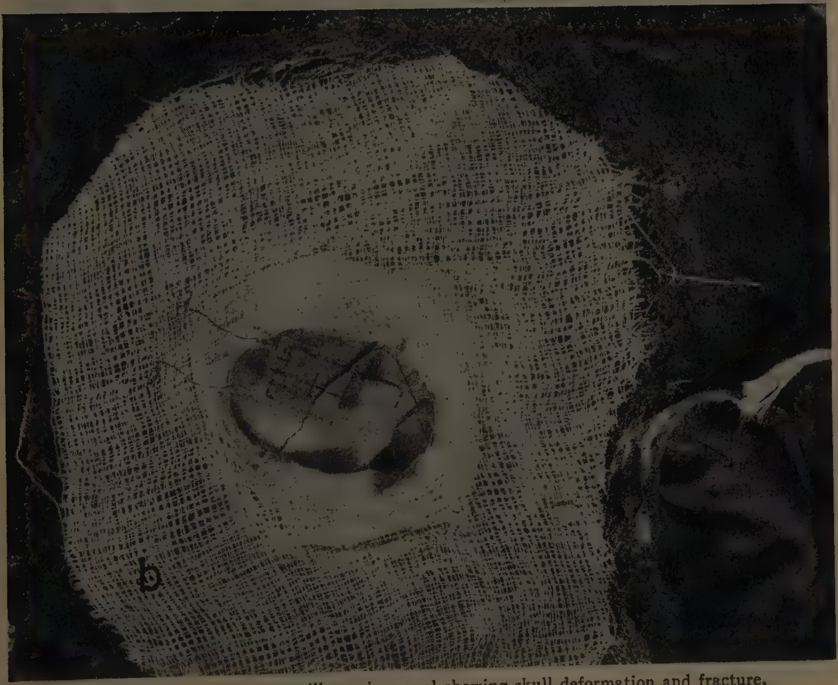


FIGURE 9a. A two-gun oscilloscopic record showing skull deformation and fracture.
FIGURE 9b. Strain gage on human cadaver head (after Gurdjian, Webster, and Lissner, 1950a).

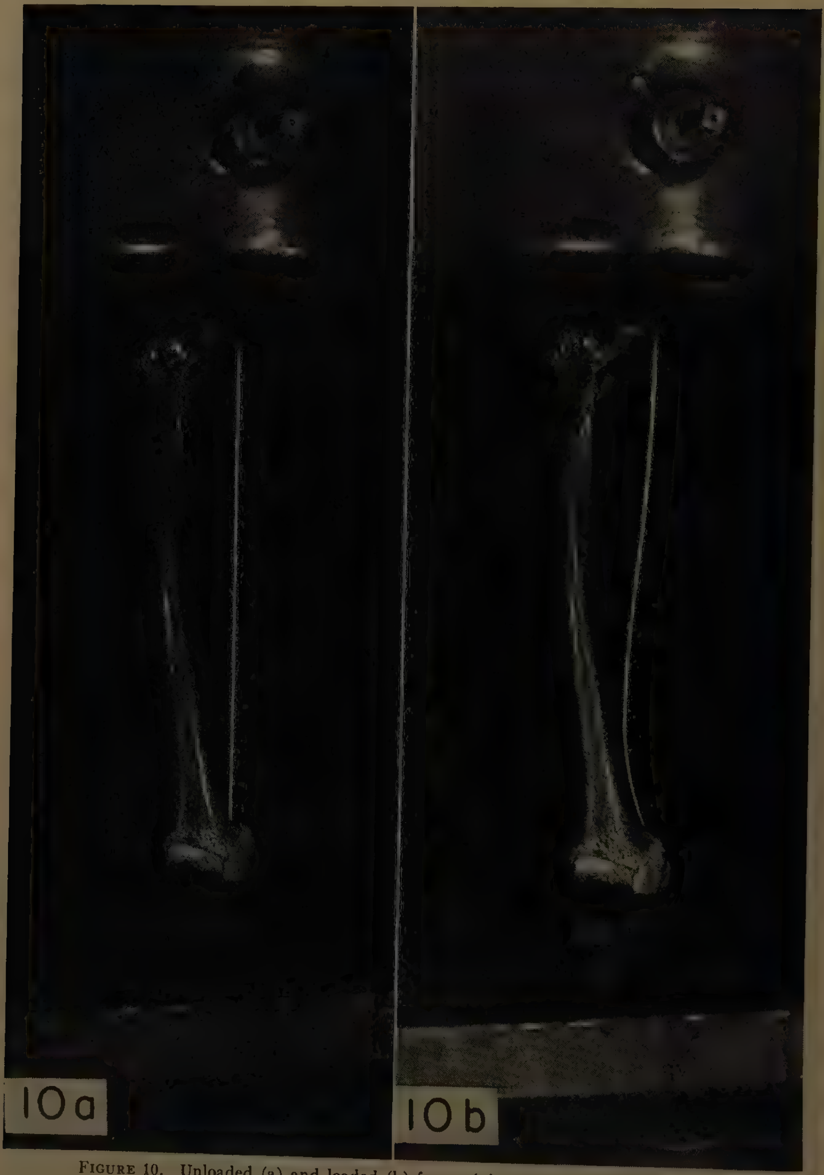


FIGURE 10. Unloaded (a) and loaded (b) femur (after Evans and Lissner, 1948).

The bending of a femur under a gradually increasing load was also visualized by watching the development of the Stresscoat pattern. The first cracks in the neck appeared on its superior aspect just distal to the head, while the corresponding cracks in the shaft were found on its lateral aspect a short distance distal to the greater trochanter. With increasing load, other cracks appeared more distally along the neck and the shaft as the bone bent under the load applied to its head.

By proper use of the Stresscoat technique it is possible to demonstrate simultaneously, in the same bone, the areas of tensile and compressive strain produced during a single test. This is done by static loading of the Stresscoated bone in a testing machine and by permitting the bone to remain under load for half an hour or longer. With vertical loading, the bone is gradually bent by the load applied to the head. This bending creates a tensile strain pattern on the superior aspect of the neck and on the lateroanterior aspect of the shaft. Leaving the load on the bone for a time allows the Stresscoat lacquer to "creep," so

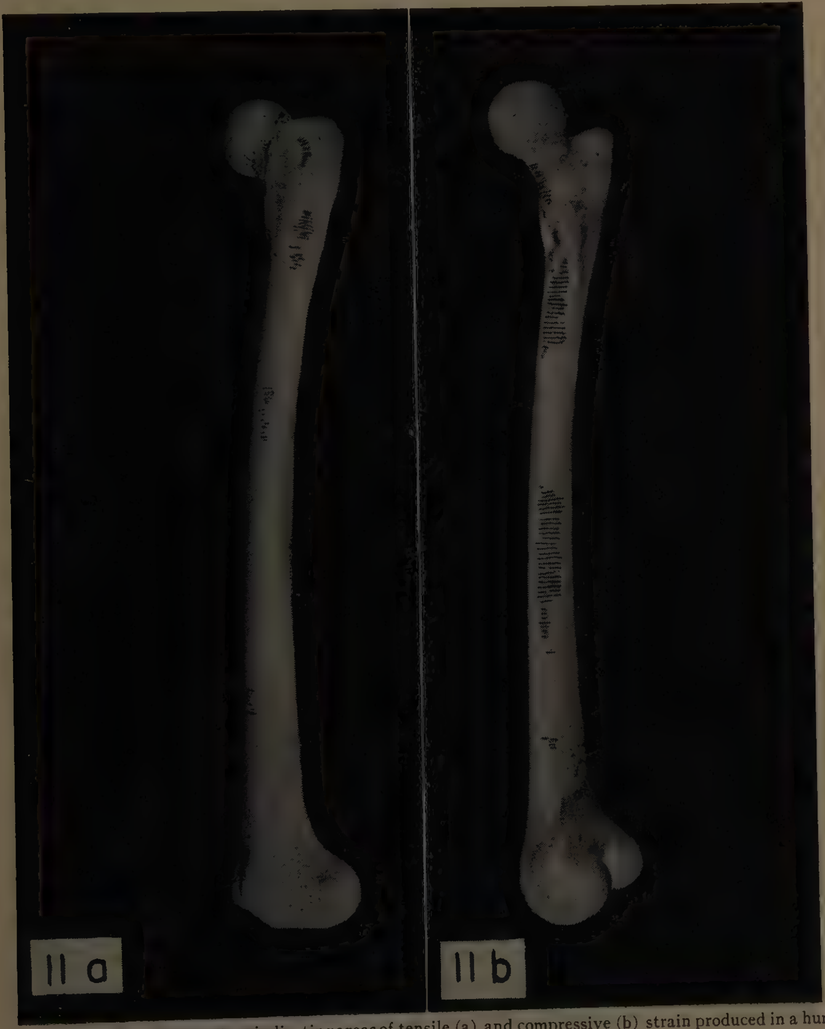


FIGURE 11. Stresscoat pattern indicating areas of tensile (a) and compressive (b) strain produced in a human femur by a static load of 240 lb.

that when the load is removed and the bone returns to its original condition, another Stresscoat pattern appears in the areas of the bone subjected to compressive strain during loading. An example of the tensile (a) and compressive (b) strain patterns produced by a load of 240 lbs. vertically applied to the head of a human femur is seen in FIGURE 11. These patterns clearly demonstrate that the femur behaved like a column subjected to eccentric vertical loading (*cf.* FIGURE 2b). Dynamic vertical loading of the femur has a similar effect (Evans, Lissner, and Pedersen, 1948).

The behavior of a femur, like that of a column loaded perpendicular to its long axis (FIGURE 2c), is evidenced by Stresscoat patterns obtained from loading the greater trochanter and the shaft. A typical example of the former is seen in the deformation pattern obtained from applying 23.7 in. lb. of energy to the greater trochanter of a femur of a white male 60 years of age (FIGURE 12). An example of the latter (FIGURE 13) was found in the strain pattern produced by application of 7.9 in. lbs. of energy to the middle of the posterior aspect of the femur of a Negro male 49 years of age. Both these patterns indicate that the energy applied to the bone caused bending with consequent tensile strain on the aspect of the bone opposite that to which the energy had been applied. Local strain patterns (FIGURE 12b) sometimes occurred at the site of impact. These patterns indicated that the force had pushed the bone thus giving rise to tensile strain in a circular direction around the site of impact. Occasionally, radially directed tensile strain also occurred at the site of impact (Pedersen, Evans, and Lissner, 1949).

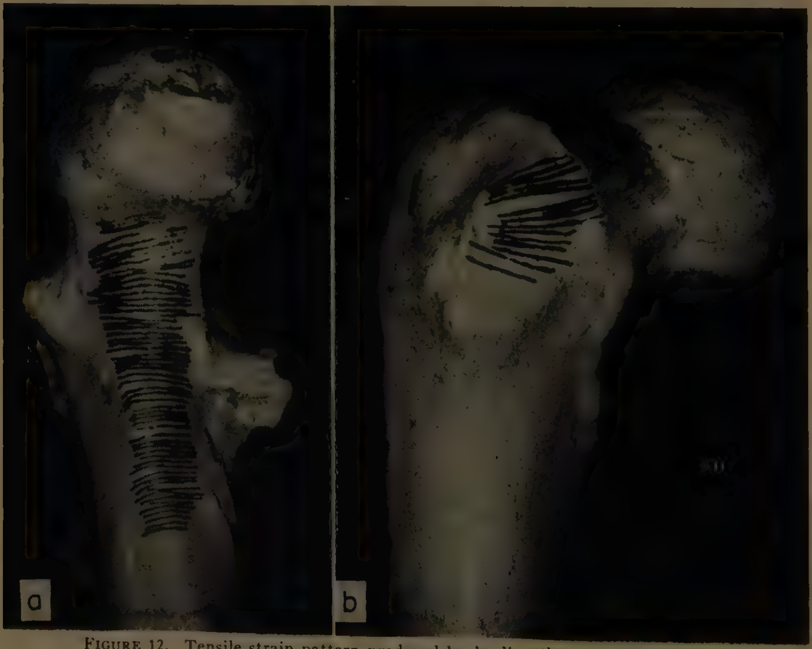


FIGURE 12. Tensile strain pattern produced by loading the greater trochanter.

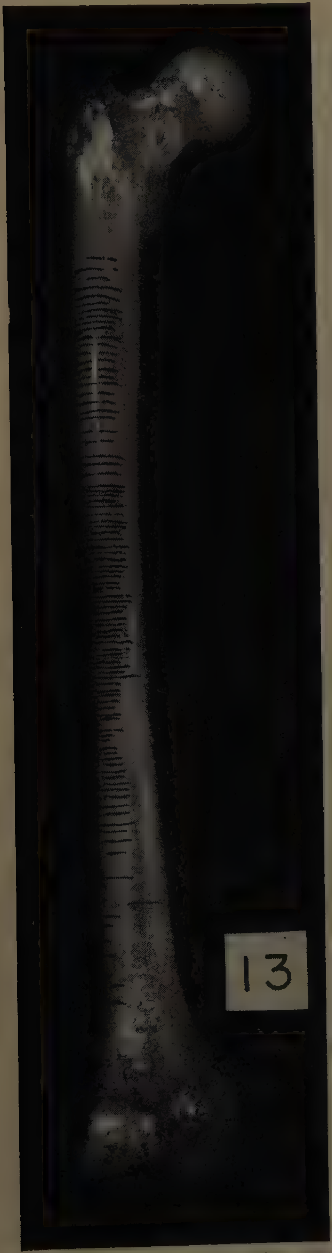


FIGURE 13. Deformation pattern arising from application of a force to the middle of the posterior aspect of the shaft.

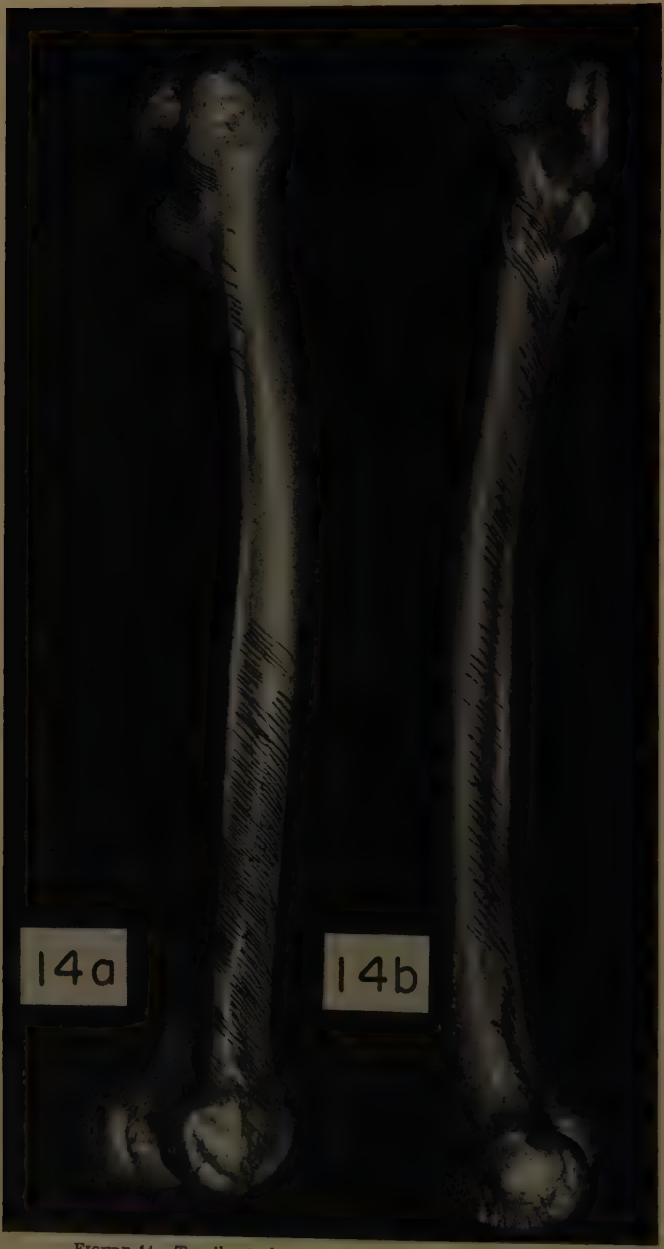


FIGURE 14. Tensile strain pattern arising from torsion loading.

Torsion loading of a Stresscoated femur demonstrates that it behaves like a column similarly loaded (*cf.* FIGURE 2d). Thus, the Stresscoat pattern produced in the femur of a white male 61 years of age by 406.5 in. lb. of torque (FIGURE 14) arose from tensile strain that spiraled around the shaft at approximately a 45° angle to its long axis. The individual cracks of the pattern also are oriented at a 45° angle to the anatomical axis of the shaft.

The tensile strain created in the femur under the above experimental conditions is of importance in the fracture mechanism (Evans, Pedersen, and Lissner, 1951; Evans, 1952). Thus, experimentally produced transverse (FIGURE 15) and oblique fractures of the neck, intertrochanteric fractures, and subcapital fractures (FIGURE 16) all arose from failure of the bone from the tensile stresses within it. The same is true of spiral or torsion and transverse fractures of the femoral shaft (FIGURE 17). The fact that these fractures are tensile failures is

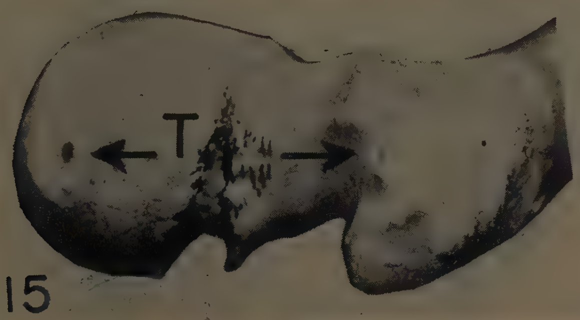


FIGURE 15. Transverse fracture of the neck produced by a statically applied load of 1280 lb. (after Evans, 1952). T = tension.

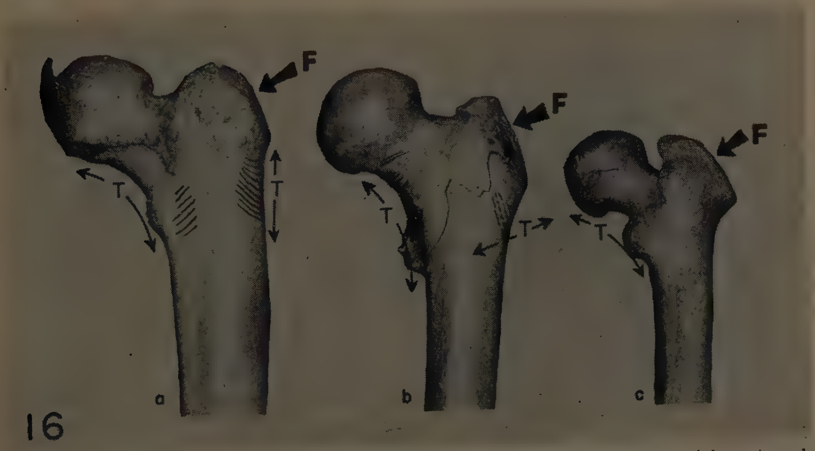


FIGURE 16. Experimentally produced fractures (from Evans, 1952). a. Oblique fracture of the neck produced in the femur of a white male 81 years of age by a load of 805-lb. b. An intertrochanteric fracture produced in the femur of a white male 85 years of age by a 900-lb. load. c. A subcapital fracture produced in the femur of white male 85 years of age by a 560-lb. load. F = point of application of force. T = tension.

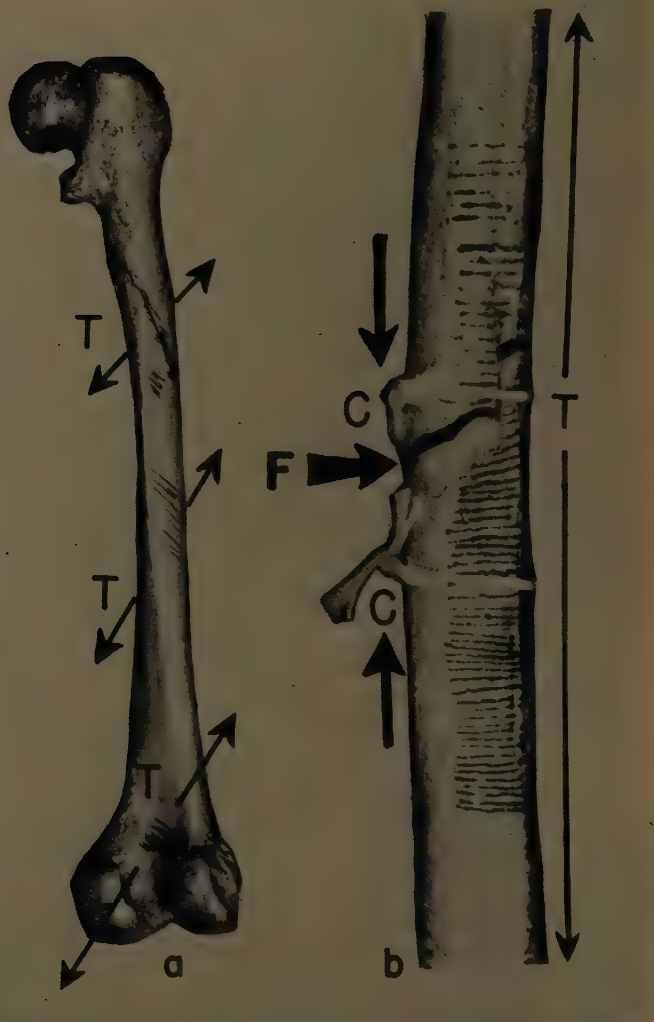


FIGURE 17. Experimentally produced fractures (after Evans, 1952). (a) A torsion fracture produced in the femur of a white male 60 years of age by 282.2 inch lb. of torque. (b) A transverse fracture produced in the shaft of the femur of a white male 79 years of age by a 390-lb. load. C = compression. F = force. T = tension.

indicated by the close agreement between the origin and course of the fracture and the stresscoat patterns on the bones. Each fracture began at the site of highest tensile strain where the first Stresscoat cracks appeared and was parallel with the cracks.

The tensile and compressive strain occurring in the tibia of a living walking dog has been recorded by means of the strain gage-oscilloscope method. In the

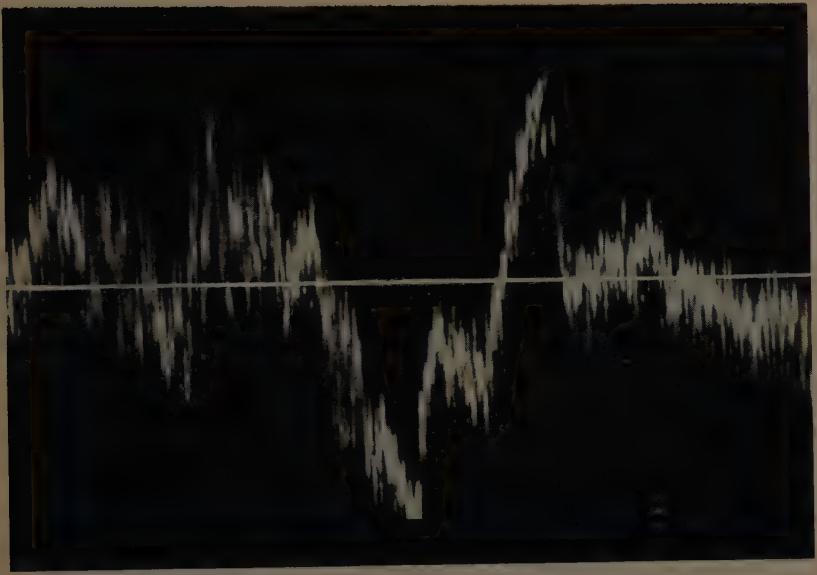


FIGURE 18. Oscilloscopic record from a strain gage on the tibia of a living dog.

oscilloscopic record (FIGURE 18) obtained by such a method the spikes above the baseline indicate tensile strain in bone, while those below it indicate compressive strain in the bone. With such a technique, accompanied by suitable calibrations of the apparatus, it is possible to measure the magnitude of the tensile and compressive strains occurring in a bone.

### *Biomechanical Behavior of the Pelvis*

Dynamic loading of the ischial tuberosities of Stresscoated pelves show that they, too, behave like an elastic body, whose deformation may be demonstrated with as little as 33 in. lb. of energy. The load was dynamically applied to the ischial tuberosities by dropping the intact pelvis upon a 160 lb. steel block. The specimen was dropped so that both ischial tuberosities struck the steel block simultaneously and was caught by hand on the rebound so that the block was struck just once. The weight of the specimen multiplied by the distance through which it was dropped gave the inch pounds of energy applied during a test.

The deformation patterns obtained in such tests show that they arise from the following displacements (FIGURE 19) of the pelvis: (1) medial or lateral rotations of the anterior-superior iliac spines; (2) medial or lateral rotations of the ischial tuberosities; (3) lateral displacement of the acetabula accompanied by posterior displacement of the symphysis pubis; and (4) various combinations of these movements.

Lateral rotation of the anterior-superior iliac spine creates tensile strain in the iliac fossa, while medial rotation of the spine causes strain in the lateral as-

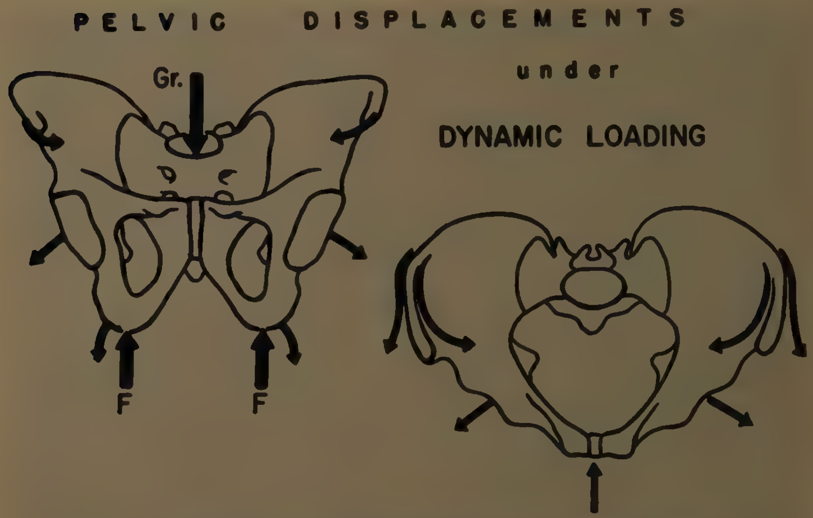


FIGURE 19. Pelvic deformations under dynamic loading (after Evans and Lissner, 1955).

pect of the iliac ala. When rotation occurs in both directions the iliac ala is subjected to a vibration or undulatory movement with consequent tensile strain on both aspects of the ala. Lateral rotation of the ischial tuberosities created tensile strain, in the long axis of the region, on the medial aspect of the ischiopubic rami. Medial rotation of the tuberosities subjects the lateral aspect of the ischiopubic rami to tensile strain. Tensile strain may be produced in both aspects of the ischiopubic rami if the ischial tuberosities rotate both medially and laterally. Lateral displacement of the acetabula, accompanied by a posterior displacement of the symphysis pubis, produces tensile strain in the long axis of the iliopubic rami as well as within the acetabula and the adjacent areas.

An example of an extensive strain pattern (FIGURE 20) arising from vibrations or undulations of the iliac alae, lateral displacement of the acetabula, and medial rotation of the right ischial tuberosity was produced in the embalmed pelvis of a white female 69 years of age by 33 in. lb. of energy, the least used in any of the tests. The presence of the sacrotuberous and sacrospinous ligaments had little effect in preventing the movements responsible for the deformation pattern. The deformation patterns produced in the few unembalmed pelves tested were essentially similar to those found in the embalmed ones, the only possible difference being that the pattern was slightly more extensive in the fresh specimens.

The influence of the mass of the head, the trunk, and the upper limbs, on the type and extent of deformations produced by dynamic loading of the ischial tuberosities in the almost intact body was studied by Stresscoating pelves in bodies from which the lower limbs and the pelvic musculature and viscera had been removed. The method of dynamically loading the ischial tuberosities was the same as previously described.

The type of deformation pattern obtained in these tests was similar to those

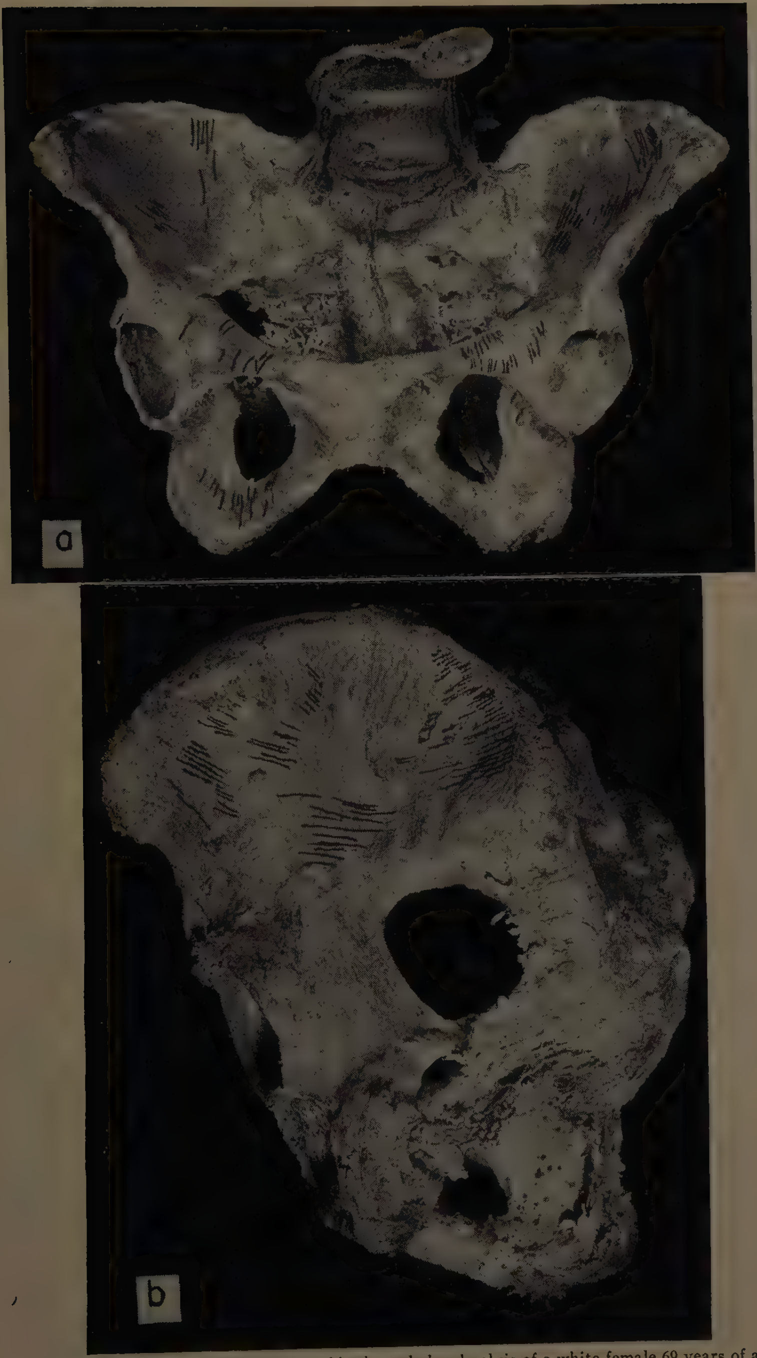


FIGURE 20. Tensile strain pattern produced in the embalmed pelvis of a white female 69 years of age by 33-inch lb. of energy.

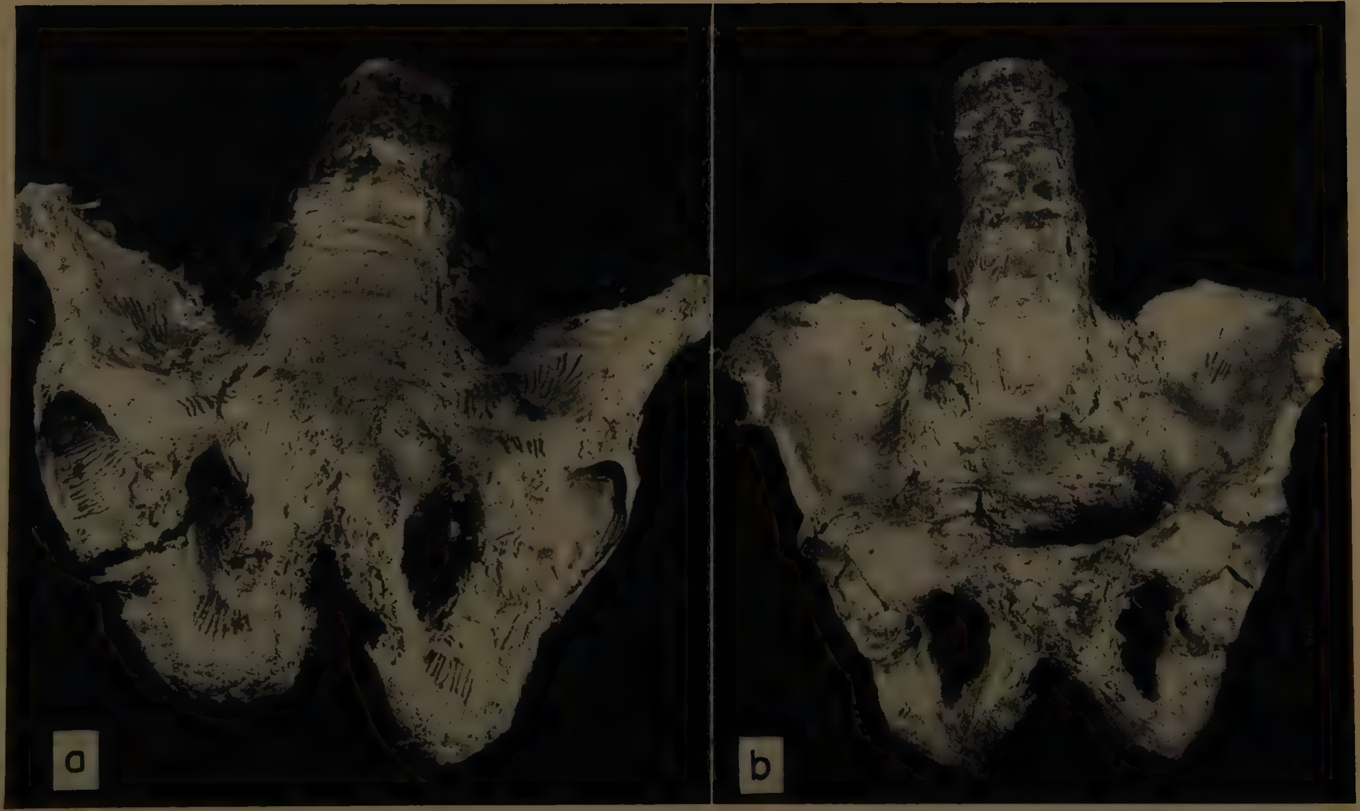


FIGURE 21. Pelvic fractures experimentally produced by dynamic (a) and static (b–d) loading (after Evans and Lissner, 1955). (a) Fracture produced in pelvis of a white male 79 years of age by 240 inch lb. of energy. (b) Fracture produced in the pelvis of a white male 60 years of age by 1350 lb. (c) Fracture produced in the pelvis of a white male 85 years of age by 373.5 lb. (d) Fracture produced in the pelvis of a white male of unknown age by 112 lb.

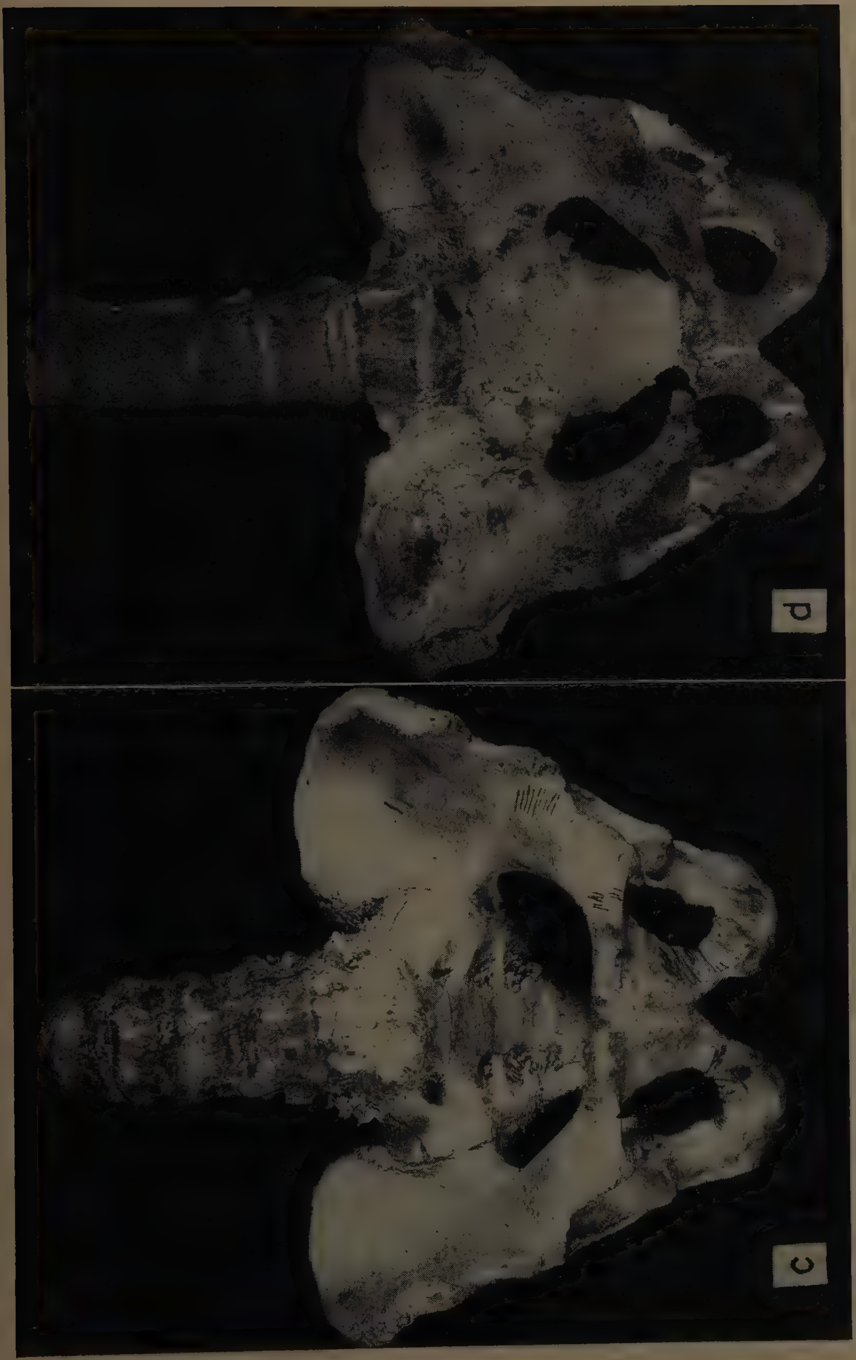


FIGURE 21 (*Continued*)

found in pelves tested after removal from the body. A few tests of the influence of soft tissue upon the extent of the deformation pattern were made by testing bodies in which some soft tissue, mostly skin and gluteus maximus muscle, was left underlying the ischial tuberosities. In one such preparation, only a minimal deformation pattern was obtained, although 450 inch lb. of energy, the most used in any of the tests, was applied to the specimen. This conforms with reports by Gurdjian, Webster, and Lissner (1949) on the energy-absorbing effect of the scalp.

Pelvic fractures produced by dynamic and static loading (FIGURE 21) showed that the fractures arose from failure of the bone from the tensile stresses within

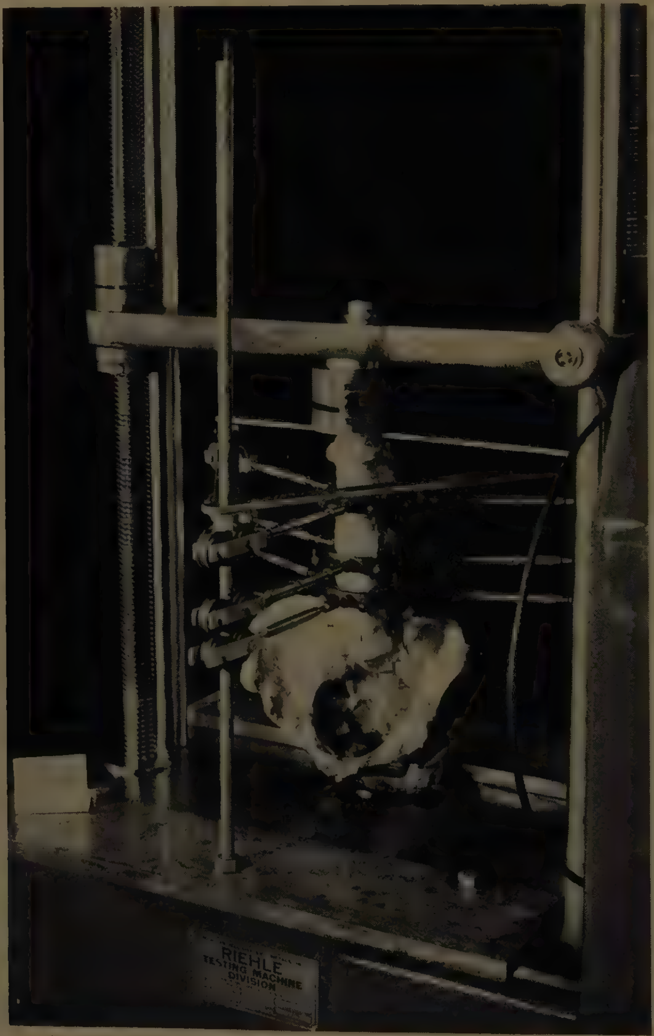


FIGURE 22. Apparatus for testing intact lumbar spine and pelvis (after Evans and Lissner, 1955).

it. This was evident from the course and direction of the fractures that corresponded closely with Stresscoat patterns obtained in the same or other pelves similarly loaded.

### *The Biomechanical Behavior of the Vertebral Column*

The deformations or deflections occurring in intact lumbar spines and pelves after removal from the body were studied by placing the specimen in a materials testing machine. A special apparatus (FIGURE 22) was designed to hold the specimen in a static position while testing. The load was slowly applied to the most proximal vertebra on the specimen until failure, as indicated by the dropping off of the load, occurred. The deflections occurring in the specimen during

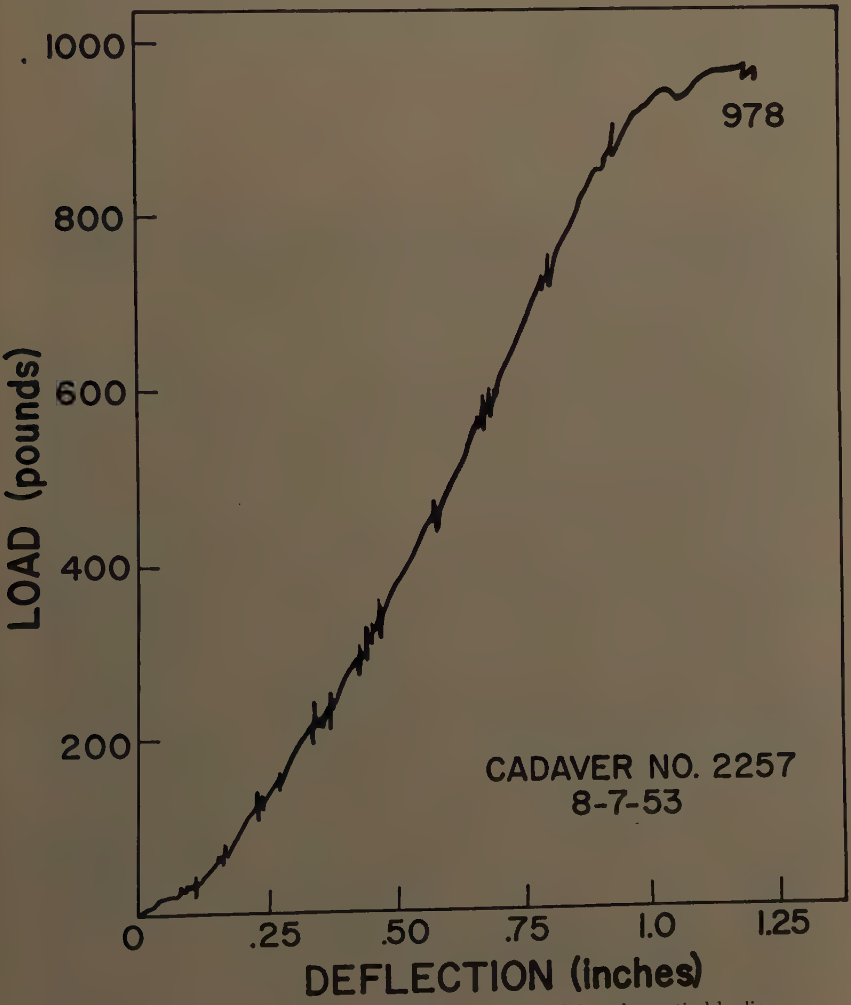


FIGURE 23. Load deflection curve for lumbar spine and pelvis under vertical loading.

a test were automatically recorded by a stress-strain recorder attached to the testing machine. The load-deflection curve produced under such conditions in the embalmed lumbar spine and pelvis of a white male 82 years of age is illustrated in FIGURE 23. Failure occurred after a maximum load of 978 lb. had been applied. In this particular specimen, the load and deflection were approximately proportional until more than 800 lb. had been applied, after which the deflection increased more rapidly than the load. The maximum deflection was approximately 1.25 inches.

For studies of the influence of flexion on the lumbar spine, a special apparatus was constructed (FIGURE 24). The apparatus was designed to accomodate specimens of various lengths and to permit orientation of the specimen so as to simulate flexion of the spine in any plane. The specimen was tested under static loading in a testing machine while the deflections were automatically recorded by a stress-strain recorder. In some instances, strain gages connected with a strain gage recorder were cemented on individual vertebrae so that a record for the strains occurring in them could be taken.

The load deflection curve produced by anterior flexion in the lumbar spine of

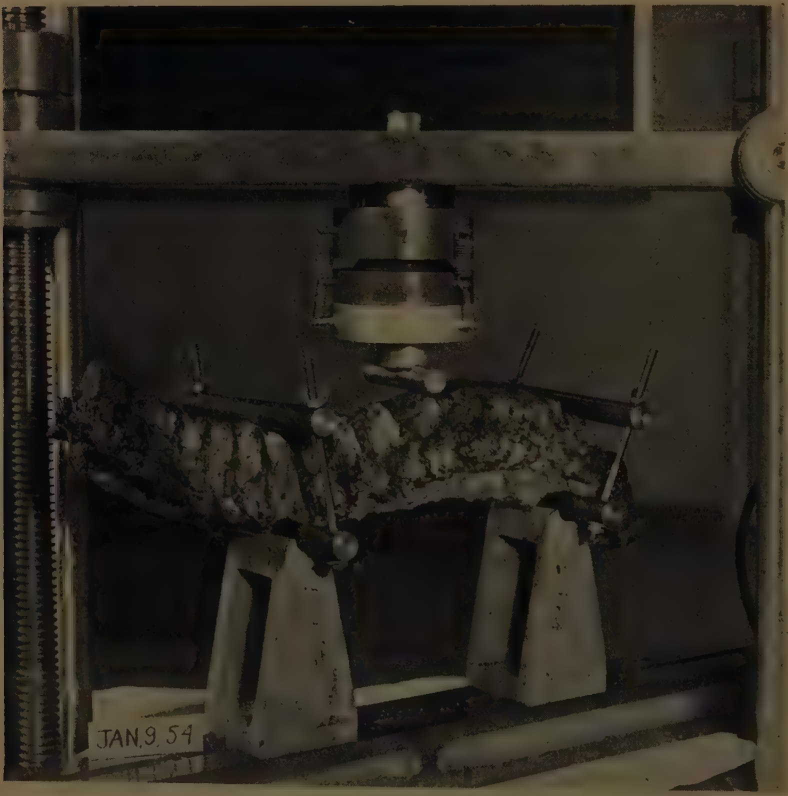


FIGURE 24. Apparatus for bending tests on vertebral column.

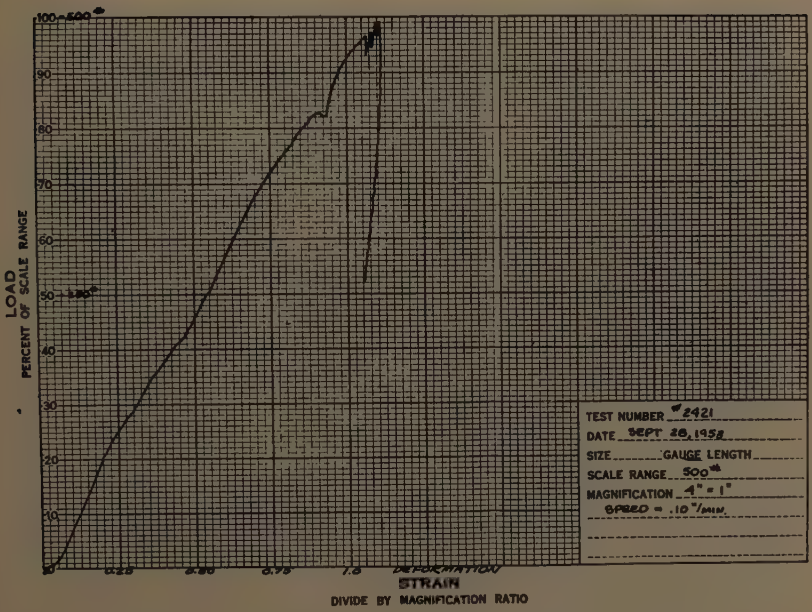


FIGURE 25. Load deflection curves for lumbar spine under anterior flexion.

a 79-year-old white male by a maximum load of 495 lb. is seen in FIGURE 25. It is seen that load increases more rapidly than deflection. The maximum deflection was 1.09 inches. FIGURE 26 is the load deflection curve produced by lateral flexion in the lumbar spine of an individual 82 years of age, to which a maximum load of 495 lb. had also been applied. In this specimen, deflection increased rapidly at first and then the load increased more rapidly than deflection up to the failure point. A falling off of the load occurred at about 200 lb., but the specimen continued to accept load until the final failure point. The maximum deflection was 0.825 in. In some of the specimens tested under bending in various planes, the deflection increased much more rapidly than the load, and a maximum deflection of approximately 2 in. was obtained.

### *The Influence of Moisture*

An important factor affecting the biomechanical behavior of bone and, especially, its energy-absorbing capacity is its degree of moisture. This has recently been investigated by Evans and Lebow (1951), who found that while drying generally increases the tensile strength and the modulus of elasticity of compact bone, it reduces its energy absorbing capacity. This is clearly shown (FIGURE 27) by a comparison of the stress-strain curves to failure of a wet and dry specimen of standardized size of compact bone taken from the same region of the shaft of the human femur. The shaded area beneath the stress-strain curve of each specimen indicates the energy it absorbed to failure. Thus, while drying increases the tensile strength of bone, its energy-absorbing capacity is tremendously reduced.

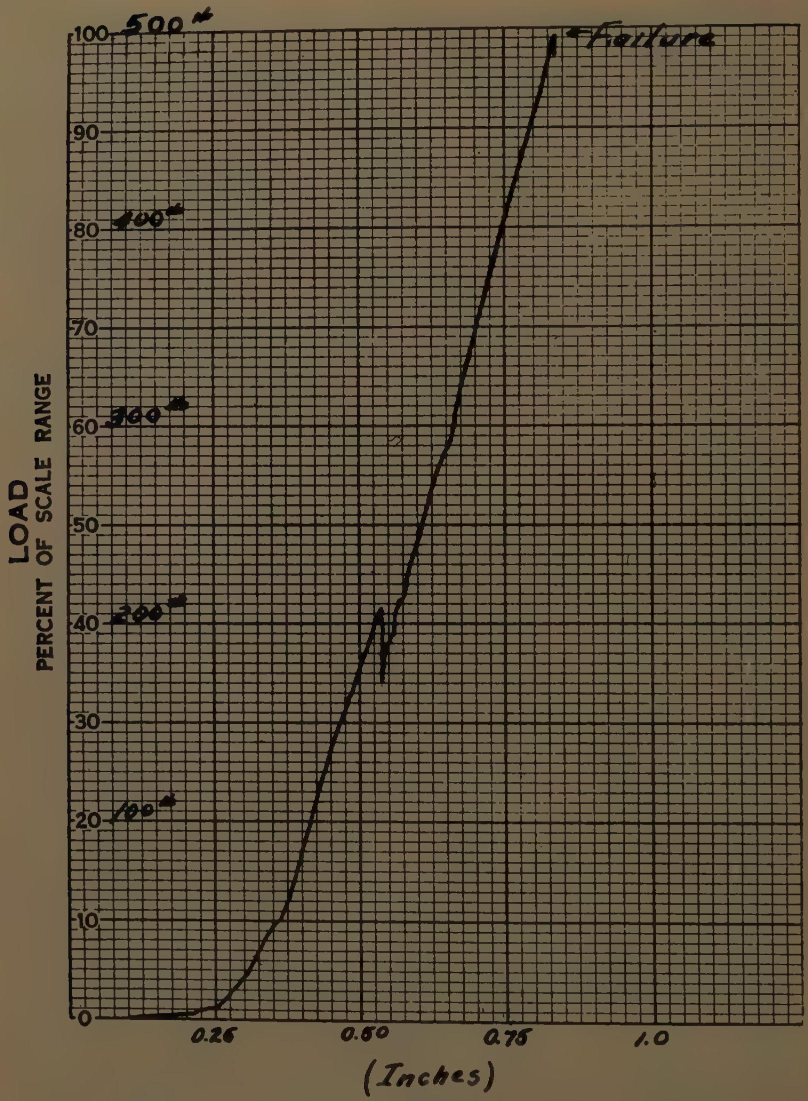


FIGURE 26. Load deflection curves for lumbar spine under lateral flexion.

The elongation that bone may undergo under tension is also a good criterion of its energy-absorbing capacity. This was shown by Evans and Lebow (1951), who plotted the per cent elongation under tension of all of the dry and all the wet samples from the femur of a 78-year-old white male against the energy (inch lb./in.$^3$) each sample absorbed to failure. A straight line relationship (FIGURE 28) between the per cent elongation and inch lb./in.$^3$ of energy absorbed to failure was found for both the dry and the wet samples. However, the slope

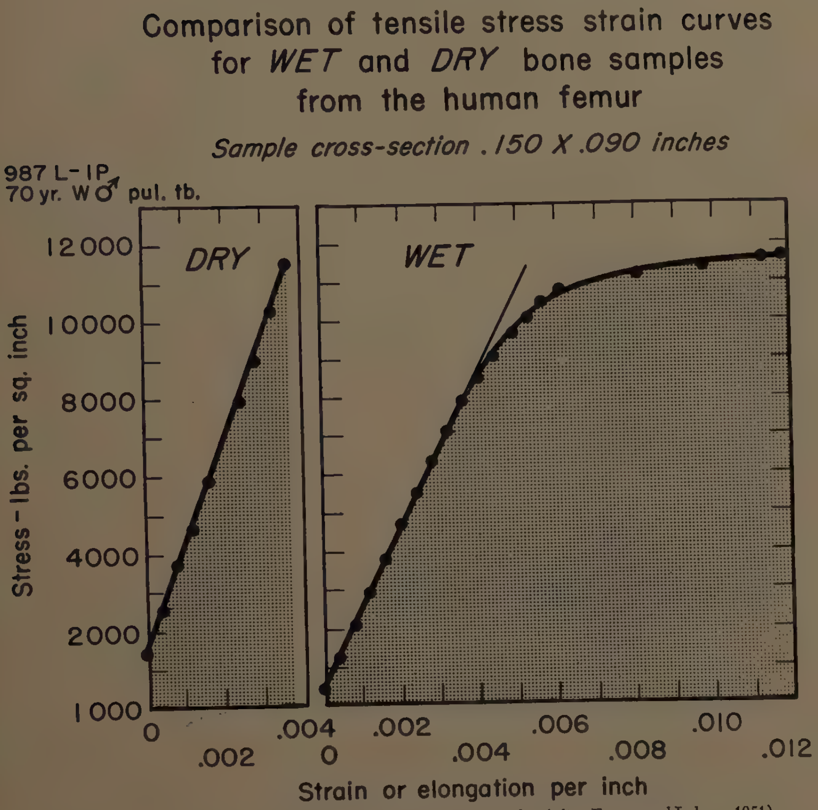


FIGURE 27. Stress-strain curves for wet and dry bone samples (after Evans and Lebow, 1951).

of the curve for the wet specimens was less steep than that for the dry specimens indicating the greater energy absorbing capacity of the wet specimens. The importance of this with respect to fractures of bones in the living body, most of which result from impacts, is obvious.

## *Summary and Conclusions*

Stresscoat deformation studies on the intact skull, pelvis, and femur indicate that all three bones behave as elastic bodies, whose deformations can be indicated with relatively small amounts of energy or load. Each bone, as long as its elastic limit is not exceeded, returns to its original dimensions after removal of the load. In the case of the femur, the areas subjected to tensile strain under static or dynamic vertical loading are the superior aspect of the neck and the lateral aspect of the shaft. When the load is applied to the shaft perpendicular to its long axis, the opposite aspect of the bone is subjected to tensile strain. Torsion or twisting of the femur creates tensile strain that spirals around the shaft of the bone at approximately a 45° angle to its long axis.

The magnitude of the apparent tensile stress (lb./in.$^2$) produced by transverse

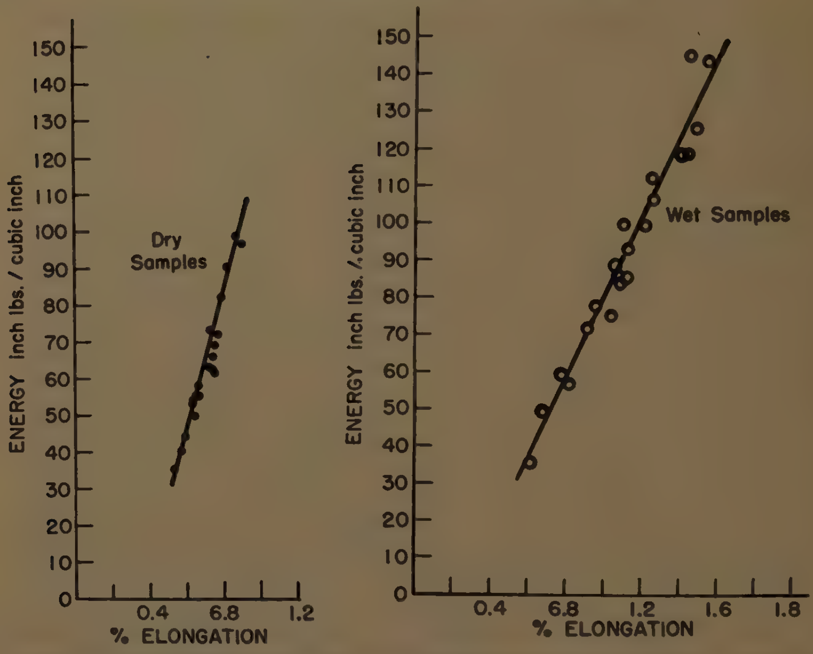


FIGURE 28. Relation between per cent elongation of a bone specimen and the energy absorbed to failure (after Evans and Lebow, 1951).

loading of the shaft of the femur has been computed by Evans, Hayes, and Powers (1953). They found that a maximum tensile stress of 2430 lb./in.$^2$ was produced in the medial aspect of the bone from applying a load to the one quarter point of the lateral aspect of the bone. Loading the posterior aspect of the shaft produced the least tensile stress in the opposite anterior side of the bone.

Experimentally produced fractures of the stresscoated skull, pelvis, and femur revealed that all linear types of fractures arise from failure of the bone because of tensile stresses within it. The close correspondence between fractures seen clinically and those experimentally produced in Stresscoated bones indicates that the former also are a result of failure of the bone because of tensile stresses within it. The tensile strain patterns produced in Stresscoated dry and living bones are essentially similar, indicating that the conclusions regarding the mechanical behavior of bones based upon Stresscoat studies of dry bones can safely be made. Bending is the most dangerous type of action for a bone because it causes tensile stresses and strains that may lead to fracture.

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# SOME CONTRIBUTIONS OF APPLIED PHYSICAL ANTHROPOLOGY TO HUMAN ENGINEERING

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The term "human engineering" can mean many things to many men. The field is new and in flux, and the definitions published in the past few years remind one of John Godfrey Saxe's poem about the six blind men of Indostan and their several descriptions of the elephant. Without arguing the merits of any of these definitions, and to achieve common understanding, if not agreement, I shall simply state my view that human engineering should mean fitting the machine to the man and keeping him functioning with efficiency, with safety, and without discomfort, in any environment.

From this general standpoint, I shall present briefly the results of three unpublished studies in applied physical anthropology, each relating to different aspects of the human being. The first will summarize the engineering use of the percentile curve as a tool to improve the sizing of work space, clothing, or personal equipment. The second will outline how the use of muscle-strength data can improve human safety and ease of machine operation. The third will attempt an answer to the question, "What happens to the buttocks when you sit on them?"

## (*1*) *The Engineering Use of the Percentile Curve*

There are two concepts of design of spaces where human beings perform work. We may call one the concept of the "average man"; the other, the concept of "design limits, or range of accommodation."

(*a*) *The concept of the "average man."* The concept of using the "average man" is nearly universal among designers. In my experience, two assumptions usually underlie this concept, the first being that only the arithmetical average or mean for any dimension of the population is needed for work space design, and the second is that human bodily proportions are generally constant, so that a short man must be only a reduced facsimile of a tall one. Let us examine these assumptions.

The arithmetical average (or mean) can be calculated from the range of any dimension taken on a human sample and, in an adequate sample, the figure describes the central tendency of the sample for that dimension. When used with a measure of variability, such as the standard deviation,* the mean provides a valid representation of the sample in comparison with other samples for the same dimension. Such a use is entirely legitimate, and it is done daily in descriptive biological science. But it is a fallacy to use merely the "average" as the basis of design for human accommodation.

If the pure average were used for, say, arm reach from the operator's body position to a control lever, only the larger 50 per cent of the population could reach the control adequately. The smaller man would be handicapped at all times, and the smallest might not reach it at all. Who would want such conditions in an emergency? In some situations, moreover, the decrease in the number of dependable operators might be serious, as actually happened in World War II.

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* A number designating the probable inherent variability for a given dimension of any number in the group. The mean plus and minus three standard deviations (called sigma) gives the limit of a normal curve encompassing about 99.7 per cent of the range.

A few years ago, a study was made by Daniels and Churchill[16] to test the assumptions of the concept of the "average" man. They examined the records of more than 4,000 United States Air Force flying personnel to find how many men could be average in 10 dimensions useful in clothing design. Instead of using the exact average, the authors make a very generous allowance of plus and minus 15 per cent from the exact average. This is the middle 30 per cent of the sample for each dimension. This they called the "approximate average." These investigators used these approximate averages of each of the dimensions as hurdles in a step-by-step elimination.

The following passage is quoted from their report. Only the percentage table has been added.

| | *Per cent of original sample* |
|---|---|
| (1) Of the original 4063 men, 1055 were of approximately average *stature* | 25.9 |
| (2) Of these 1055 men, 302 were also of approximately average *chest circumference* | 7.4 |
| (3) Of these 302 men, 143 were also of approximately average *sleeve length* | 3.5 |
| (4) Of these 143 men, 73 were also of approximately average *crotch height* | 1.8 |
| (5) Of these 73 men, 28 were also of approximately average *torso circumference* | .69 |
| (6) Of these 28 men, 12 were also of approximately average *hip circumference* | .29 |
| (7) Of these 12 men, 6 were also of approximately average *neck circumference* | .14 |
| (8) Of these 6 men, 3 were also of approximately average *waist circumference* | .07 |
| (9) Of these 3 men, 2 were also of approximately average *thigh circumference* | .04 |
| (10) Of these 2 men, 0 were also of approximately average *crotch length* | .00 |

The percentages show that by the third hurdle the number of "approximately average" men had shrunk to an insignificant 3.5 per cent and at only the fourth, the relative number, 1.8 per cent, is for practical purposes at the vanishing point.

The fact that these figures represent an exceedingly generous middle 30 per cent of the population for each dimension make the demonstration even more convincing. Nor are these dimensions chosen for this purpose. Any other set would have shown the same results.

Thus it must be clear that the assumptions of the "average man" concept are fundamentally incorrect because no such creature exists. Work spaces, to be efficient, should be constructed on the basis of design limits chosen according to the range of body size found in the using population.

(*b*) *Selection of design limits.* The "design limits" concept is not the brainchild of any one person. It has grown out of the hard experience of many men, both in this country and abroad. During World War II, Randall, Damon, and other anthropologists[1] at Wright Field were, so far as I know, the first in the United States to realize and act on the need for design limits based on the population to be accommodated. Since then, the realization has made headway with further commentary by Randall,[1, 2, 3] Hooton,[4] Morant,[5] Weddell and

Darcus,[5] McFarland and his collaborators,[6, 7] King, Morrow, and Vollmer,[8] and Coakley, Fucigna, and Barmack,[9] to name but a few. But because the "average man" concept continues to confront anthropologists at every turn, some explicit summary of the "design limits" concept seems necessary.

To exemplify this method, we may take a fighter airplane cockpit whose plastic canopy is just high enough to cover the pilot's head as he looks about. Obviously head position must be nearly constant for every pilot, hence the small man must adjust his seat upward, the large man must adjust it downward. The vertical dimension of the cockpit and the adjustability of the seat are governed by several bodily dimensions, one of which is sitting height—the distance from the top of the head to the surface on which the subject sits erect. How shall we choose design limits for this cockpit?

If we measure a large random Air Force sample for sitting height, we can list each man's dimension in numerical order to find the range of variation. By standard statistical procedures, the total range of dimension can be divided into 100 equal parts called percentiles. The 95th percentile is that value that includes 95 per cent of the population, above which extends the remaining 5 per cent. The percentile table for sitting height[15] is presented in TABLE 1, and the percentile curve that can be drawn from it is shown in FIGURE 1.

We see immediately that there is a fairly straight-line portion comprising approximately the central 90 per cent of the sample and that, on both ends, there are two shoulders of sharply increased slope, each about 5 per cent of the sample.

The curve also shows that in the present Air Force sample, nude sitting height varies from 29.9 to 41.2 inches, or 10.3 inches. The extremes of any percentile curve, however, are highly unstable, being strongly affected by one or a few very large or very small persons in the sample. Statisticians usually base normal curves on the mean ±3 sigma, or 99.7 per cent of the range, but the design engineer not familiar with statistics may find it simpler for his purposes to deal with the 98 per cent group falling between the 1st and 99th percentile (here, the mean ± approximately 2.9 sigma). It can be seen that the variability of the 98 per cent drops to only 6.0 inches.

TABLE 1

PERCENTILE VALUES FOR SITTING HEIGHT OF AIR FORCE FLYING PERSONNEL

| Percentile | In. | Percentile | In. |
|---|---|---|---|
| 1 | 32.9 | 55 | 36.1 |
| 2 | 33.3 | 60 | 36.3 |
| 3 | 33.5 | 65 | 36.5 |
| 5 | 33.8 | 70 | 36.6 |
| 10 | 34.3 | 75 | 36.8 |
| 15 | 34.6 | 80 | 37.0 |
| 20 | 34.9 | 85 | 37.3 |
| 25 | 35.1 | 90 | 37.6 |
| 30 | 35.3 | 95 | 38.0 |
| 35 | 35.5 | 97 | 38.3 |
| 40 | 35.6 | 98 | 38.6 |
| 45 | 35.8 | 99 | 38.9 |
| 50 | 36.0 | | |

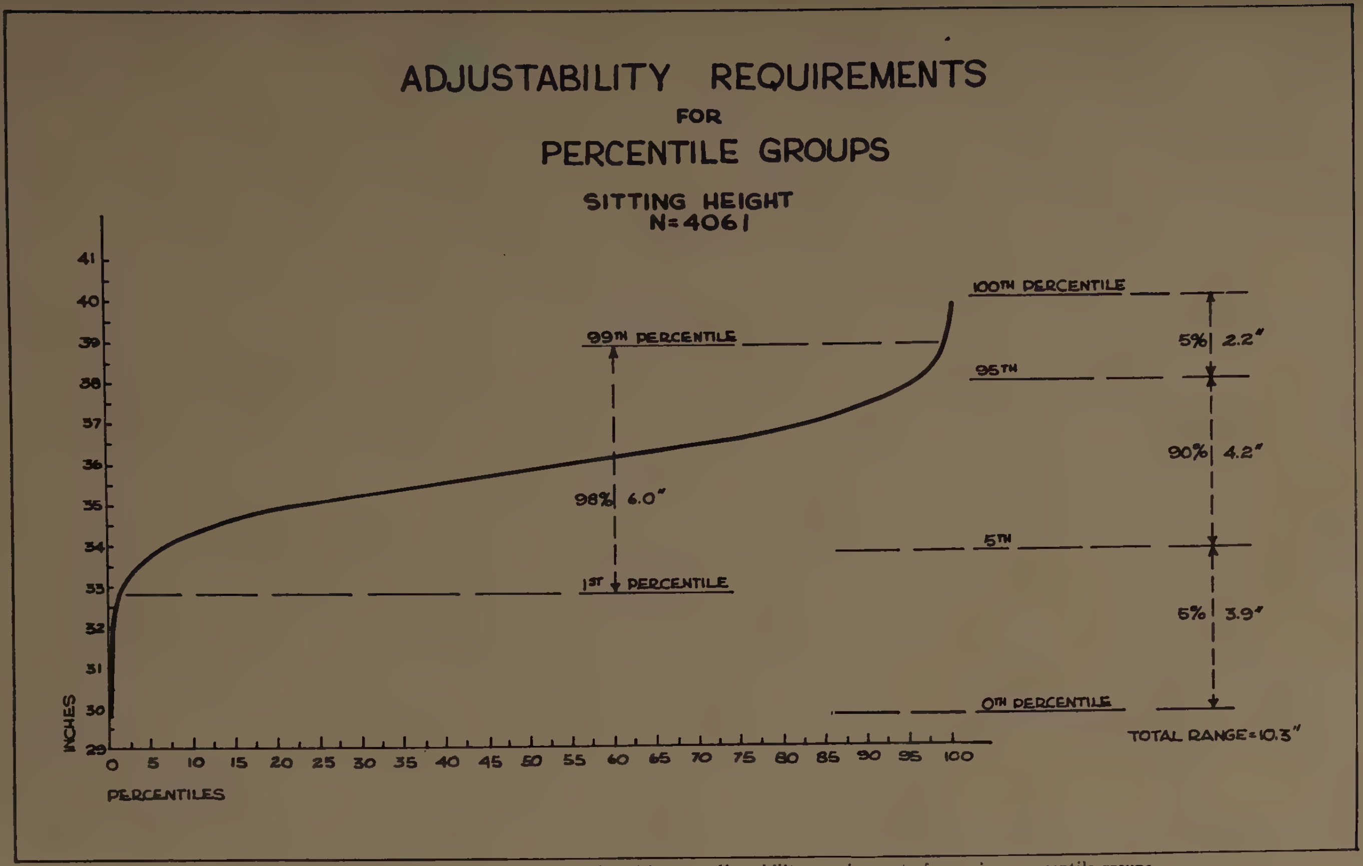

FIGURE 1. The percentile curve for sitting height with seat adjustability requirements for various percentile groups.

TABLE 2

| Per cent of sample (N = 4061) | Variability | Adjustability required |
|---|---|---|
| | *inches* | % |
| 100 | 10.3 | 100 |
| Largest 1% (99th to 100th percentile) | 1.4 | 13.6 |
| Largest 5% (95th to 100th percentile) | 2.2 | 21.3 |
| Central 90% (5th to 95th percentile) | 4.2 | 40.8 |
| Smallest 5% (0th to 5th percentile) | 3.9 | 37.9 |
| Smallest 1% (0th to 1st percentile) | 3.0 | 29.1 |

The variability for each percentage segment indicated in FIGURE 1 can be summed up in TABLE 2.

It seems unnecessary to labor these figures, as they speak to the designer for themselves. In brief, however, if we consider adjustability to accommodate the entire sample, then the extreme 10 per cent of the men require about 60 per cent of the total adjustability, while the remaining 90 per cent of the men need only about 40 per cent. It is also interesting to note that the combined variabilities of the extreme 2 per cent practically equal that of the central 90 per cent. Inasmuch as adjustability costs weight and space, as well as money, this table shows the relative expense of accommodating different segments of the population.

It is here that the aircraft cockpit designer must exercise judgment in the choice of design limits. Aircraft builders have learned that for every pound added to the cockpit, at least 10 pounds more are needed in the air frame to carry the extra load. Weight and space are therefore at a premium because both so markedly affect aircraft performance.

All this explains why there is a general rule in Air Force design of cockpits, flying clothing, and personal equipment, that each piece of equipment must accommodate at least 90 per cent of the personnel, and also why equipment accommodating more than 90 per cent may be given another hard look to be sure that it does not cost more in weight and space than it is worth. Experience shows that if this rule is followed, the remaining 10 per cent can also get along with the equipment, though they may have to accept some extra discomfort, especially the last 2 per cent.

But any such rule must be applied with caution, because many factors affect a decision. One factor is the number of sizes of an article. Airplanes, for example, are too expensive to build in more than one size for each model. Obviously, it would be uneconomical to size the fighter cockpit for the largest man. The excess weight would penalize the performance of all airplanes of that model and their pilots. It is better to require that the 98th percentile man hunch down to the 90 per cent cockpit or even to bar him from the fighter type aircraft. Oxygen masks, on the other hand, have hitherto been furnished in three sizes. Here it is necessary to fit—at any rate, to keep alive—100 per cent of the flying population, though this goal is not achieved without some alteration of equipment for certain persons and some discomfort among persons with unusual facial size and shape. Thus the designer must try to balance all the factors over which he has control, and to recommend the best compromise in the specific situation.

To summarize, by means of proper anthropometric data and analysis, the designer can produce small sizes of his product for small men, or large sizes for large men. Conversely, if he is limited for some valid reason to a given size or adjustability, he can determine the population percentage the product will accommodate.

The provision of space that is enough for the using group of operators, but neither more nor less, is a major purpose of human engineering.

### (2) *The Design Use of Muscle-Strength Data*

After we have sized the cockpit to proper dimensions, we encounter problems relating to another aspect of the man.

The pilot exerts his will only through his muscle strength. There are numerous types of levers in the combat aircraft cockpit. A few of these are the stick to control direction of flight, the throttle to control power, and even a special trigger that, when squeezed by the pilot's hand, sets in a motion a mechanism of automatic escape from the aircraft in emergency. The human engineering requirements of this last system deserve a closer look.

Let us assume that an ejection seat is being designed. This is a seat that can be catapulted out of a disabled aircraft, carrying the pilot along. To eject himself, the pilot must erect the triggering mechanism from where it is normally folded on the arm of the seat, and with his right hand squeeze a movable trigger toward a fixed bar. The designer wants to make the pull as heavy as possible to minimize accidental actuation. Should he design the trigger to be tripped by a man of "average" strength? If he does, the weaker half of our pilots will never escape from the aircraft. The designer's dilemma constitutes an apparently simple muscle-strength problem: how much force can a man exert by a squeeze of his hand?

Reflection on the problem shows that other factors are involved. If the fingers are like other body segments, then there is a position of the fingers, as they close on the palm, where the force they can exert is at a maximum. Hence dimensions of the gripping mechanism become a factor as well as muscle strength. Consequently it is necessary to conduct our research with a dynamometer whose separation distance is variable between the palm and the inner surfaces of the fingers.

FIGURE 2 shows the Smedley-type variable dynamometer chosen for the purpose. The variability of the movable member, or trigger, from the fixed member, or "heel" in this instrument ranged only from about 1¼ inches to 3 inches, not enough for the test desired. Therefore two wooden spacers were fabricated so as to extend the trigger-heel distance. Each subject was requested to exert a maximum barehanded squeeze at separation distances of 1½, 2½, 4, and 5 inches.*

For practical Air Force purposes, however, another variable entered here.

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* The 5-inch distance, though clearly excessive, was included because a previous trigger handle design used that distance.

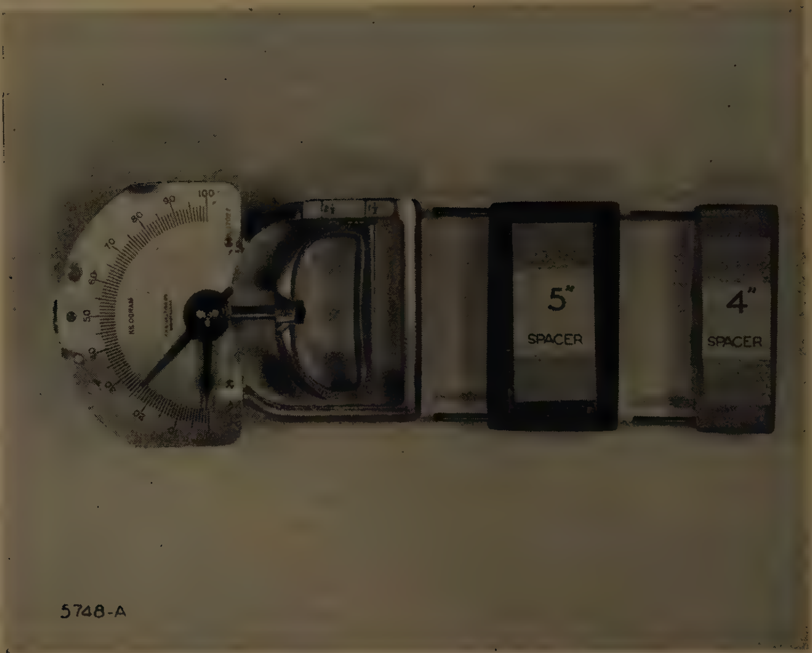

FIGURE 2. Smedley type hand dynamometer with spacers.

Every combat pilot must wear gloves as protection against flash fires and also against cold in emergency. Therefore each subject repeated every trial while wearing properly-fitted gloves, taking eight trials in all. To guard against fatigue effects, several subjects were gathered at the same time, and each performed the same test in turn. This provided ample recovery time between trials, usually about 20 minutes. Forty-four subjects, all pilots, were used in the test.

The results are tabulated in FIGURE 3. Every subject exerted more force at the 2½-inch separation distance than at any other, and every subject's force decreased about 20 per cent as a result of wearing gloves. Now obviously this does not mean that 2½ inches is the best separation distance for all hands, large and small. It does mean that the 2½-inch distance was closer to the optimum separation distance for each hand than any other distance tried. But 2½ inches becomes an acceptable basis for any design that must permit maximum strength application over a wide range of hand size. Thus we have answered one part of the designer's question.

As to the force to be required of the pilot to actuate the ejection trigger, the reasonable answer here is to take the force exerted at 2½ inches by the weakest subject while wearing gloves. In such a test, of course, with a relatively small sample, it is necessary to select a sample that is representative of Air Force body size.

Aside from the specific answers to the seat designers, I think this test has implications for anthropologists, orthopedists, and others interested in measuring and comparing human muscular performance.

The foregoing results throw some doubt on grip-strength comparisons made heretofore, because the separation distances are unknown. Standardization of the entire procedure seems to be in order. Even measurements taken on the Collin elliptical dynamometer would come into question, because the curved surfaces produce different separation distances for different fingers. This may well reduce the effectiveness of application of the subject's potential gripping strength. Research to determine the most efficient forms of instruments for all muscle-strength measurements appears necessary.

This principle of lever design for maximum ease or mechanical advantage of actuation has many applications. It is essential, of course, in modern aircraft, where speeds mount and the time available for pilot reaction grows correspondingly less. In the cockpit, every control must be "human-engineered" for maximum integration of pilot and machine—anything less becomes too costly. But industrial machines also have many controls, and it is only a matter of time until all levers will be properly sized and put at the best locations, to operate at the forces that most people can exert on them. The reduction of human fatigue and inefficiency should be great.

### (3) *What Happens to Buttocks When We Sit on Them?*

We come now to our third example, the problem of seating. This problem is amazingly ramified. The angle of the seat pan, the angle of the back, the angle enclosed between them, the dimensions of each portion, the height of the

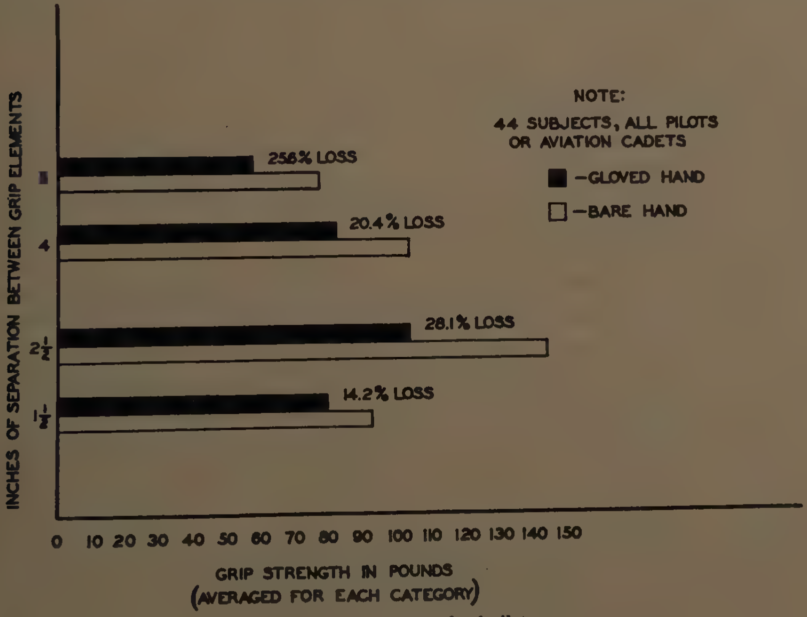

FIGURE 3. Grip strength of pilots.

seat off the floor, the location of the foot pedals or rests (for no working seat is complete without them), the location of the arm rests, the quality and form of cushions, the firmness of the materials, the duration of occupancy—all these and many more affect the satisfaction an occupant gets from his seat. In addition, the equilibrium between all these details can change radically if the occupant's duties, or his body position, change. So it is not astonishing that the seat problem is still with us, especially in aircraft where the pilot is subjected to the additional mental stress of supersonic speeds at altitudes where he knows he cannot live without unfailing protective equipment.

Of all the studies that have been made, probably the remarkable paper of Lay and Fisher, "Riding Comfort and Cushions," published in 1940,[10] has had the most pronounced effect on the engineering world. Randall, Patt, and their colleagues, during World War II, studied aircraft seating[1, 2] using the Lay and Fisher technique, and Henry,[11] Lippert,[12] and others have added their contributions to pilot seat and cushion accommodations. Hooton[3] studied seating for a builder of railway seats, and Akerblom[13] published an analysis of seating from the anatomical viewpoint. Recently, McFarland, Damon, and their collaborators[7] studied truck-cab accommodations, pointing out some serious deficiencies in those vehicles. Thus the problem has not been ignored. In most of these studies, though not all, the underlying assumption was that if the seat dimensions were right, the occupant's discomfort would be largely eliminated.

It cannot be denied that this is at least a first approximation to the truth. Much seating discomfort has stemmed from incorrect angles and faulty dimensions. But when all these have been corrected, the occupant still complains of buttock discomfort, especially if he must occupy the seat for extended periods of time. Are these complaints due to the sheer immutable cussedness of the human animal, or has some factor been overlooked?

The search for a means of reducing buttock fatigue raised the serious question, just what does happen to the buttocks when you sit on them? This is difficult to answer, for one cannot normally see the buttocks when they are sat upon and, even if one could, the discomfort occurs inside, with few external traces. Breaching the epidermal defenses of the buttocks by needles or other electromyographic devices would destroy their integrity, and would alter the physiological equilibrium by inserting a different kind of pain. Clearly any empirical investigation along these lines would have to be indirect. Perhaps pressure measurements might be a first step.

Of the authors listed above, only a few had tried to measure buttock pressures. Lay and Fisher, with their ingeniously contrived "Universal Test Seat," measured the displacement of springs in their seat cushions and calculated the buttock and back loads. Buttock load over a 17 × 18-inch area was found[10] to follow a curve showing a peak load under the tuberosities of about 0.4 pounds/inch$^2$. In this test seat, each spring covered an area of 9 square inches. Randall,* using a copy of the Lay and Fisher machine during World War II, found the peak for pilots to be 1.09 pounds/inch$^2$.

These loads certainly seemed low enough to be painless, yet personal experi-

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* Unpublished data in Anthropology Section.

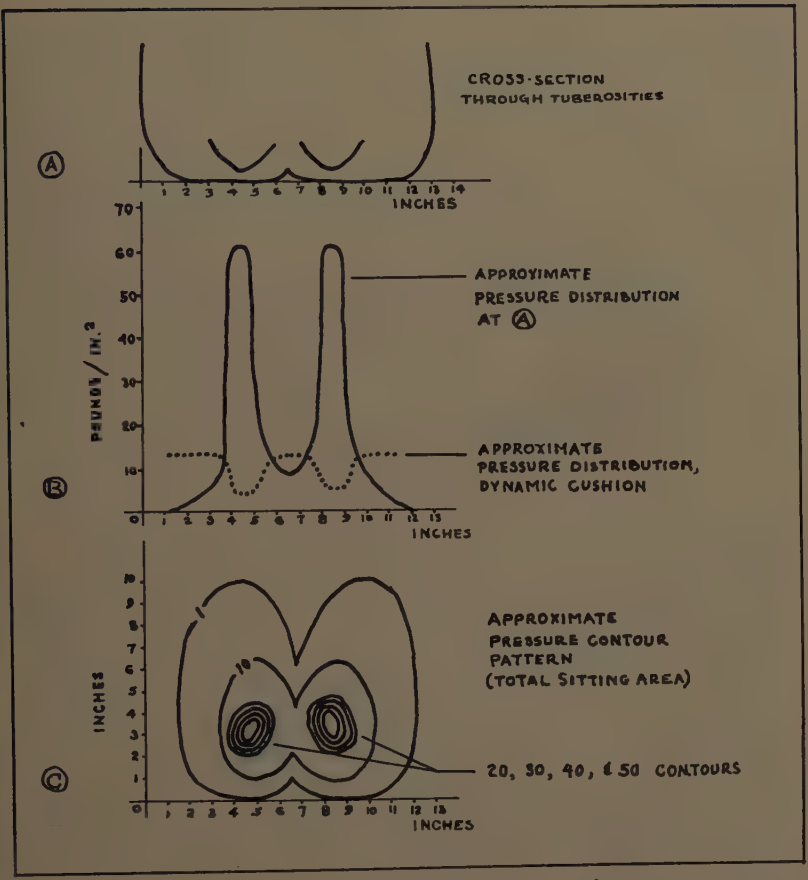

FIGURE 4. Assumed conditions in seated buttocks.

ence during tests of numerous cushions and types of seats proved that severely painful areas or "hot spots" do develop under the ischial tuberosities. This forced the subjective belief that there must be rather high pressure under the tuberosities changing to low pressures in the peripheral areas. How to demonstrate them was the question.

Let us consider FIGURE 4. The top sketch (A) shows a cross section of the buttocks sitting on a flat seat ruled off in inches. The tuberosities are sketched in place. If the subjective belief were true, the pressure curve at this cross section would be somewhat as shown in sketch (B)—low at the sides of the buttocks, higher under the tuberosities.

If we draw pressure contours of such a condition we obtain the load map of the surface somewhat like (C). Buttock flesh cells so compressed and deprived of fresh blood might very well be a part of the severe pain resulting when one sits long in one position. Why not build an inflatable cushion to this design?

The problem was taken up by C. A. Dempsey, an industrial designer, and

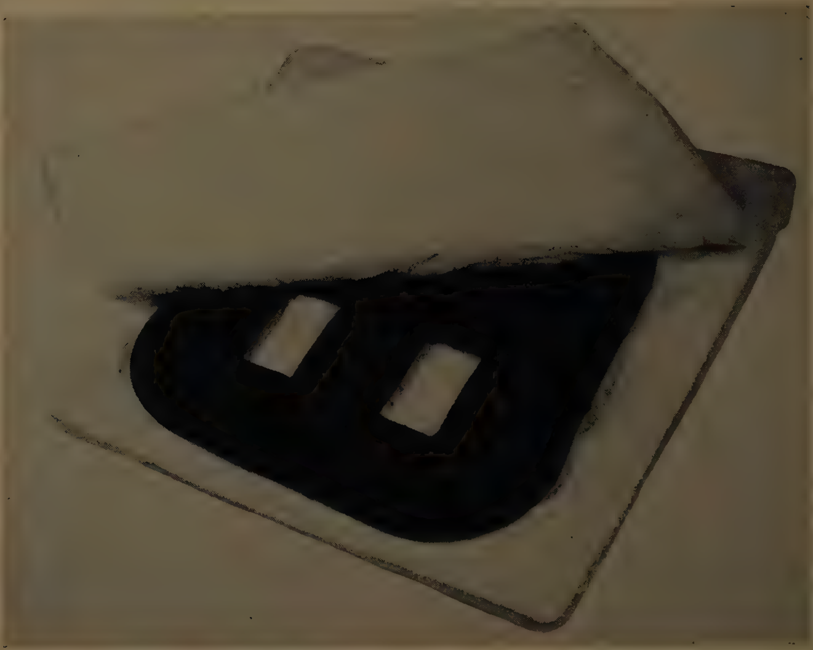

FIGURE 5. Cut-away view of dynamic cushion (showing inflatable bladder).

Lieutenant Nina K. Morrison, biologist, and an article was constructed and tested. We measured the distance between a few pairs of tuberosities as a beginning. After much development, an article called the "dynamic, inflatable cushion" was produced (see FIGURE 5) which consists essentially of a single bladder with cut-out holes under the tuberosities sandwiched between sheets of foam rubber. The bladder is inflated and deflated in a 40-second cycle through a special valve (not shown here). The uninflated cushion leaves the full load on the tuberosities. The pressure distribution upon inflation is as shown in the dotted line of Sketch (B) of FIGURE 4. When inflated to about 1½ pounds per square inch, the bladder increases the load on the peripheral flesh and lifts it slightly, just enough to drop the load under the tuberosities to zero or nearly so. There is an adjustment on the valve for different bladder pressures to compensate for different body weights. The distance the body is lifted is so slight that the eyes probably do not move over $\frac{2}{10}$ inch and, in many cases, the movement is imperceptible. This slow alternation between load and no load has been found very effective in preventing the onset of buttock pain.

To summarize this development up to this point in the discussion, we have a cushion, so far successful. It is an example of human engineering, slightly limited as yet because we have fitted only one machine to only a few men. We are still faced with the inaccessibility of tuberosities for measurement, and we still do not know buttock loads in any accurate way. How can we "human engineer" our cushion so that it will fit all men and lift all men?

The story is not complete, but we have procured two items of equipment to do just what we need done.

The first is a device called the "C-Ray Pediscope" by its inventor, Jack McGrath, a physical therapist of Detroit, Mich. With it he diagnosed foot troubles visually. In its principle it resembles Elftman's "barograph."[14] It consists of a boxlike structure, about 2 feet cubic, whose top is a sheet of thick transparent plastic. This plastic is edge-lighted by a green fluorescent tube concealed inside the box. Underneath the plastic is a large mirror set at 45° to horizontal. On top of the plastic lies a very thin sheet of latex rubber. When the subject stands on the latex sheet, he presses it close to the plastic, causing a bright green glow in the regions of high pressure and a duller glow in the zones of lower pressure. The foot soles can be seen in the 45° mirror. This system has the advantage that the image of the foot is continuous rather than consisting of dots, as in Elftman's technique. The simplicity and utility of this machine for buttock observations is evident, but because the aircraft seating situation is more complicated than a flat, horizontal surface, a special model of the Pediscope has been constructed with adjustable back and foot rest. A

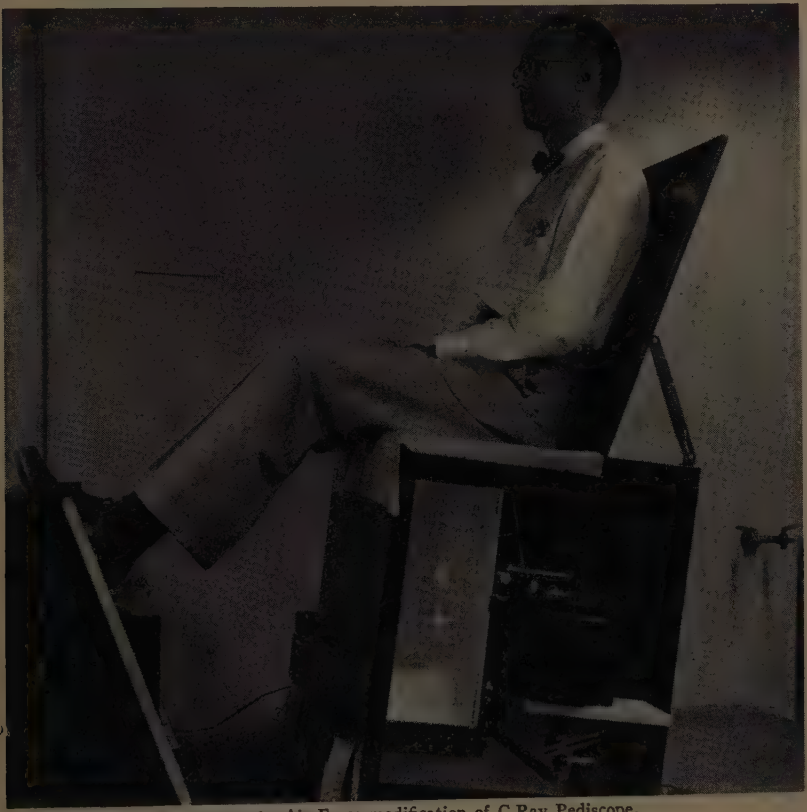

FIGURE 6. Air Force modification of C-Ray Pediscope.

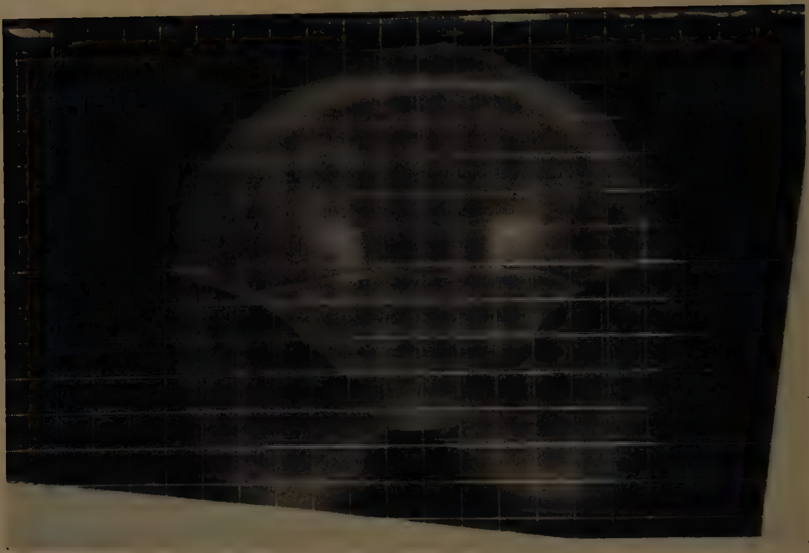

FIGURE 7. Close-up buttock pattern (seated).

larger 45° mirror has been provided to facilitate photographic recording, and the plastic sheet is lined in 1-inch squares for ease in measurement. FIGURE 6 shows the Air Force Pediscope* with a subject whose tuberosities can be perceived shining out of the buttock pattern. So now we can see the buttocks and can measure a number of things about them. A close-up of the buttocks is shown in FIGURE 7.

The second item is a so-called "pressure-measuring blanket" or "Filpip" as it is designated by the Franklin Institute whose personnel originally developed the item for the United States Army Quartermaster Corps.† This device is essentially an electronic capacitance bridge circuit, one side of which is a pad or blanket containing a number of closely-spaced, thin, flexible capacitors, each exactly 1 square centimeter in area. When compressed from their normal thickness, their change in capacitance indicates the increased pressure in pounds per square inch. The entire pad is smooth and only about 1/16 inch thick, and so can easily be placed between the tuberosity and the seating surface without causing any appreciable discomfort.

Now what do these devices show us?

The Pediscope gives us (1) the distance between the tuberosities; (2) the angle between the tuberosities; (3) the area of the tuberosity for a given seating position; (4) the location of the tuberosities within the sitting area. The pressure-measuring blanket tells us the approximate pressure under any part of the buttock area. We are conducting a buttock survey for these several classes of information. The data will be used to size the bladder and space the cutout holes in an optimum fashion for the using population. Anthropometric data and somatotype photographs are being collected on all subjects. Respecting buttock loads, we are not in position at this writing to specify pressures at the low end of the scale, because the original equipment is not sufficiently accurate between 0 and about 10 pounds for precise locations of contour lines. But it is definite that loads under the tuberosities can run in certain body types to as high as 60 pounds per square inch, and perhaps higher, thus explaining, at least in part, the severe pain that one experiences on sitting without moving for 6 to 10 hours.

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* No formal name has been given this Air Force model, but we are considering "Buttock Assessor."

† The first article was generously lent by the Quartermaster Corps to the Air Force for our preliminary tests.

The new cushion designs produced by this approach, both static and inflatable, have shown very promising results in preliminary tests. It is perhaps not too much to hope that the buttock fatigue experienced by long-range pilots, bus and truck drivers, and others, may be largely eliminated in the future. The same principles may be applied to mattresses, wheel chairs, automobiles, and many other types of chairs.

In conclusion, we have seen that a number of important practical problems can yield to the anthropological and statistical approach. Especially, it should be clear that the concept of averages is untenable as a basis for design, and that an intelligent choice of limits is the proper procedure in such widely different areas as workplace sizing, muscle-strength accommodation, or even the study of a pain in one's seat.

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# ANTHROPOMETRIC DATA IN THE DESIGN OF ANTHROPOMORPHIC TEST DUMMIES

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## *Introduction*

There has long been a need for test subjects that are human enough to provide useful information under experimental situations in which live human subjects would be endangered. Such conditions are frequently encountered in aircraft and automobile safety research, in the study of blast effects upon human operators, in ejection-seat studies, and in many similar situations. The series of anthropomorphic test dummies developed by the Alderson Research Laboratories, Inc., New York, N. Y., with which this paper is concerned, represent attempts to provide lifelike test subjects capable of meeting rigorous experimental criteria.

Because the Alderson Test Dummy seeks to simulate the basic plan of construction of the human body, but with certain appropriate simplifications growing out of intended applications and fabrication requirements, anthropometric data are essential in its design and provide the limits within which its motions are possible.

From a historical point of view, the Air Development Center of the United States Air Force at the Wright-Patterson Air Force Base at Dayton, Ohio, has been particularly concerned with the design and application of test dummies. The United States Navy's Air Development Center at Philadelphia, Pa., has also made extensive use of anthropomorphic test dummies, and it was under the sponsorship of this center that the Mark III Alderson Test Dummy was developed. The Civil Aeronautics Authority has also found the test dummy of value in its studies, and several important developments in this field may be traced to efforts of research workers in the civilian field.

The Air Development Center in November 1949 set forth in great detail a set of requirements for the body and torso of test dummies to be developed, setting the weight at 200 pounds, establishing centers of gravity of the torso, the amounts of movement, *etc.* TABLE 1 indicates the weight distributions for body members proposed.

Because of the intended use of the dummies, the Air Development Center specified that all appendages to the torso be attached strongly enough to withstand disruptive forces of 100 g in any direction. They proposed that the chest cage also be capable of withstanding instantaneous impact loads of 100 g without permanent distortion. The toughness of the outer covering or skin of the dummy was to approximate that of human skin.

Using the above specifications, and many not cited here, the Sierra Engineering Company of Sierra Madre, Calif., developed an anthropomorphic test dummy that substantially satisfied the Air Force criteria.

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* The author was related to work on the Alderson Test Dummy while he was Director of Human Engineering at the Alderson Research Laboratories, Inc., New York, N. Y.

TABLE 1
WEIGHT PERCENTAGES OF BODY MEMBERS

| Member | Per Cent |
|---|---|
| Head | 6.9 |
| Torso and neck | 46.1 |
| Upper arms | 6.6 |
| Lower arms | 4.2 |
| Hands | 1.7 |
| Thighs | 21.5 |
| Lower legs | 9.6 |
| Feet | 3.4 |
| | 100.0 |

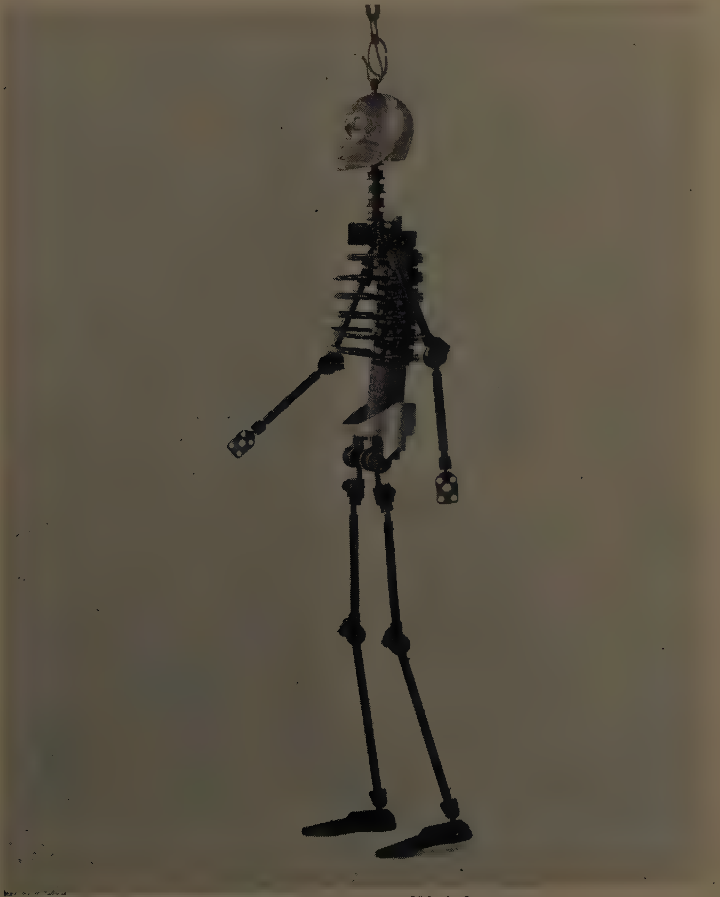

FIGURE 1. The Mark III skeleton.

### *The Alderson Research Laboratories Test Dummies*

The first in a series of three test dummies developed by the Alderson Research Laboratories represented an effort to incorporate many of the Air Force specifications, and certain additional ones, within the framework of a simpler and less expensive design and method of fabrication. The Mark III, which is the latest development, is designed to reproduce human proportions, weight distributions, articulations, resilence, and other physical characteristics that go to determine the forces that are likely to be imposed upon man in a wide variety of real life and experimental situations, the motions that he would

TABLE 2
ARTICULATIONS AND RANGES OF MOTION OF THE MARK III

| Articulation | Motion | Range *degrees* |
|---|---|---|
| Head, relative to cervical spine | Forward flexion | 40 |
| | Backward flexion | 60 |
| Cervical spine | Lateroflexion | 40 |
| | Rotation (either side) (distributed among 5 vertebrae) | 50 |
| Cervical spine relative to sternal plate | Forward flexion | 20 |
| | Backward flexion | 20 |
| | Rotation (either side) | 20 |
| Thorax relative to pelvis | Forward flexion | 40 |
| | Backward flexion | 15 |
| | Rotation (either side) | 40 |
| | Flexion distributed among 7 thoracic and lumbar vertebrae; rotation in thoracic vertebrae only | |
| Shoulders relative to torso | Rotation in all directions | 20 |
| Arm relative to shoulder | Forward flexion | 180 |
| | Backward flexion | 60 |
| | Rotation (either side) | 90 |
| | Abduction | 135 |
| Forearm relative to upper arm | Forward flexion | 145 |
| | Rotation (either side) | 85 |
| Hand relative to forearm | Forward flexion | 90 |
| | Backward flexion | 60 |
| Leg relative to pelvis | Forward flexion | 145 |
| | Backward flexion | 45 |
| | Abduction | 70 |
| | Rotation (either side) | 50 |
| Lower leg relative to thigh | Backward flexion | 135 |
| Foot relative to lower leg | Forward flexion | 30 |
| | Backward flexion | 75 |
| | Lateroflexion (either side) | 15 |

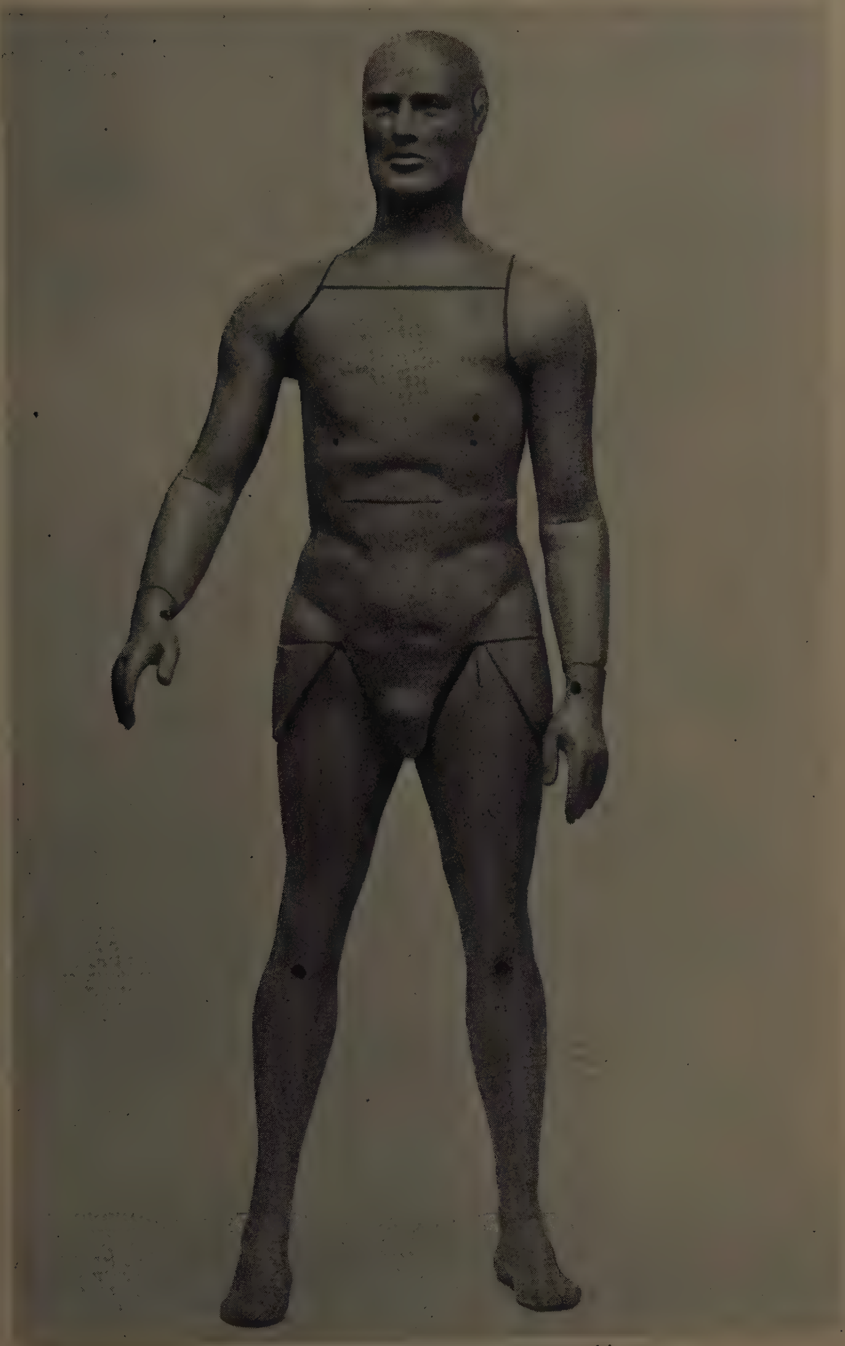

FIGURE 2. Mark III dummy in standing position.

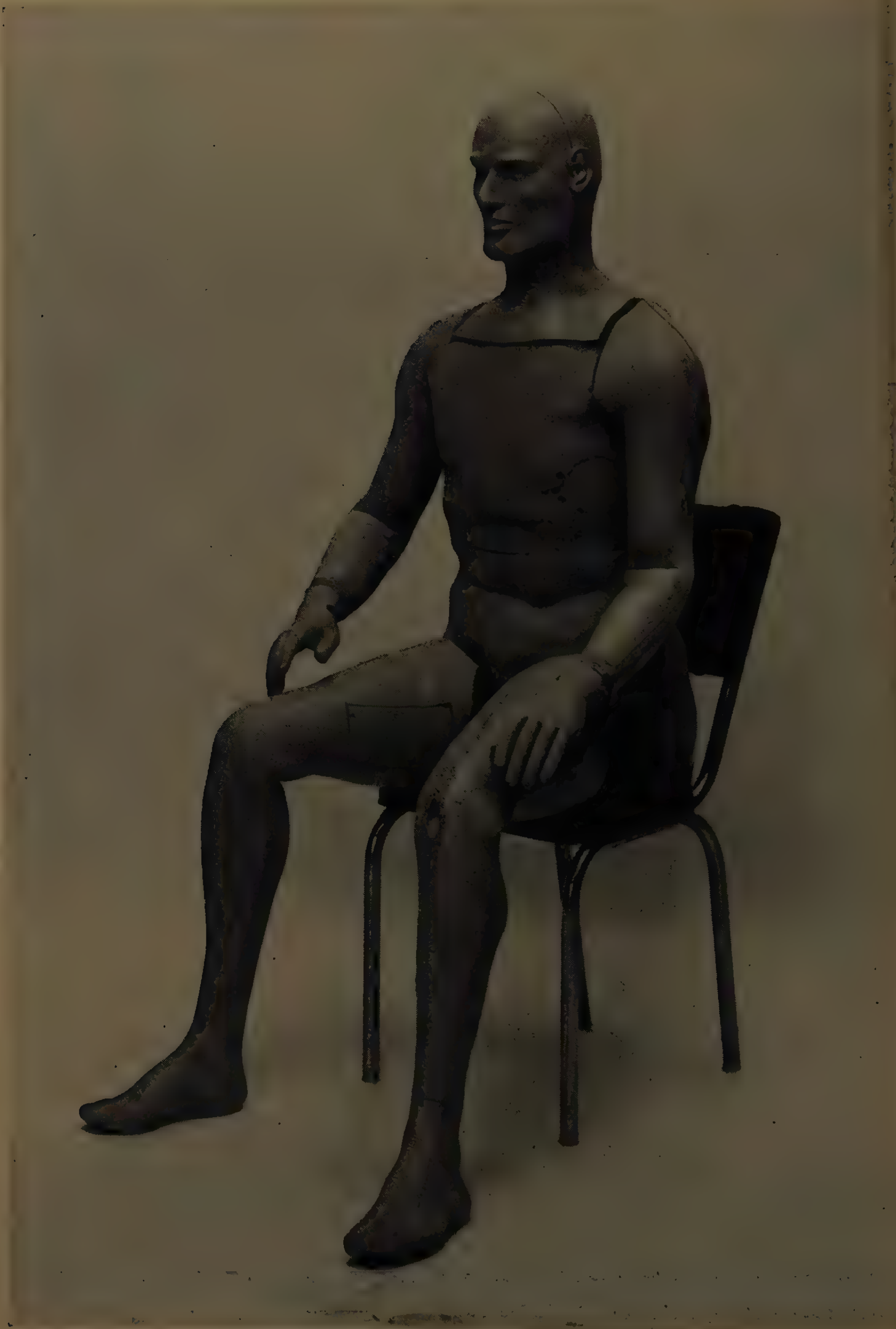

FIGURE 3. Mark III dummy in sitting position.

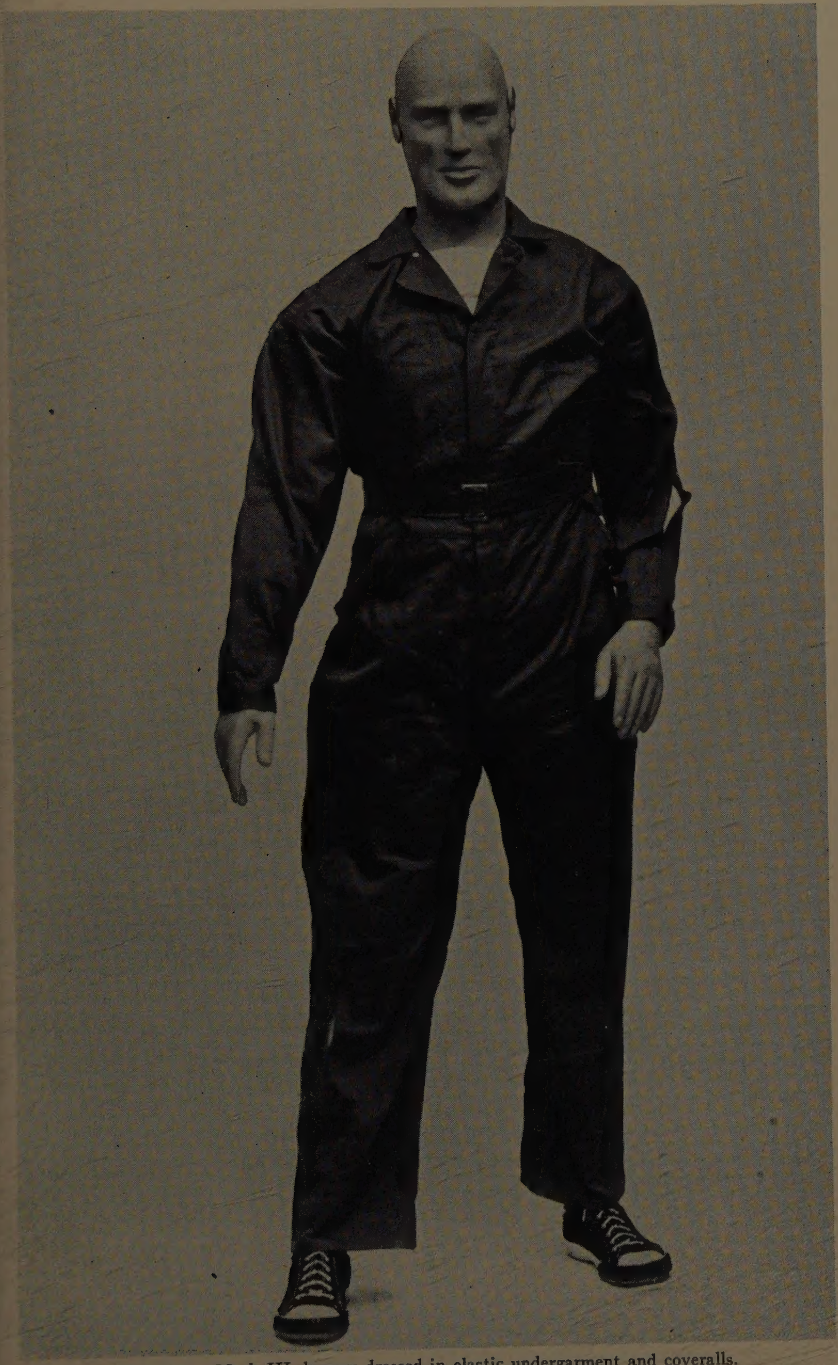

FIGURE 4. Mark III dummy dressed in elastic undergarment and coveralls.

make in response to forces playing upon him, and his terminal position and condition.

It has not been planned that Mark III would duplicate to any considerable degree the effects of physical damage that would be inflicted upon a human subject placed under the same conditions. We predicated the design of the test dummy upon the fact that actual physical and physiological response to test conditions is highly variable and needs to be treated statistically.

Against this background, let us look more closely at Mark III. The principal articulations of the human skeleton are reproduced by a metal skeleton (see FIGURE 1) that duplicates a wide range of motions with considerable fidelity. These motions and their ranges are set forth in TABLE 2. The kinematics of human joints have been simplified to pure motions about definite axes, rather than the anatomically-correct combinations of rolling and sliding motions. Such simplifications have permitted a more rugged construction with little sacrifice in the validity of data likely to issue from test procedures using the Mark III.

The Mark III Anthropomorphic Test Dummy has moulded flesh that follows the contours of a live model. FIGURE 2 indicates that the body of Mark III is asymmetrical, as with the human prototype. Skin and flesh have been designed to correspond with a human body in a moderate state of muscular tension.

The dummy is 6 feet 0 inches high, and has a total weight of 200 pounds. In general, Mark III corresponds to weight distributions set forth in TABLE 1 above for its various members, and the center of gravity of each member corresponds to data developed at the Wright-Patterson Air Force Base. FIGURE 3 shows Mark III in a sitting position.

## *Conclusion*

An effort has been made to embody a wide variety of pertinent anthropometric data in the design of an anthropomorphic test dummy that may be used experimentally in greatly different situations. Mark III has actually been employed under many circumstances in which physical data have been recorded by means of visual observation, high-speed motion pictures, and instruments employing telemetering. Data resulting from the application of the test dummy in such experimental situations have been reduced and compared with pertinent physical and physiological data from other sources to provide a forecast of the probable consequences of such experiences upon live human subjects. Used in this manner, Mark III has become an important factor in man-machine studies in extrahazardous environments, and has opened up new avenues of research by substituting the machine shop for the hospital in the event that tests become too severe.

FIGURE 4 showes the finished Mark III Dummy.

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